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SPONSORED PROJECT INITIATION

Date: 7/26/80

Project Title: Continued Development and Application of Some Fast Neutron Dosimetry Techniques Utilizing Plastic Track Detectors for Radiotherapy and Health Physics

Project No: E-26-655 (Continuation of E-26-642)

Project Director: Dr. Karl Z. Morgan

Sponsor: Department of Energy; Oak Ridge Operations; Oak Ridge, TN 37830

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CA-3 (3/76)

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SPONSORED PROJECT TERMINATION

Date: January 23, 1981

Project Title: Continued Development and Application of Some Fast Neutron Dosimetry Techniques Utilizing Plastic Track Detectors for Radiotherapy and Health Physics

Project No: E-26-655

Project Director: Dr. Karl Z. Morgan

Sponsor: Department of Energy; Oak Ridge Operations; Oak Ridge, TN 37830

Effective Termination Date: 11/30/80

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CA–4 (1/79)

DEVELOPMENT AND APPLICATION OF THE ELECTROCHEMICAL ETCHING TECHNIQUE

Annual Progress Report
(Contract No. DE-AS05-76EV04814)

August, 1980

School of Nuclear Engineering
Georgia Institute of Technology
Atlanta, Georgia 30332

TABLE OF CONTENTS

1. SUMMARY

This annual progress report documents further advances in the development and application of electrochemical etching of polycarbonate foils (ECEPF) for fast, intermediate, and thermal neutron dosimetry as well as alpha particle dosimetry. The fast (> 1.1 MeV) and thermal neutron dosimetry techniques were applied to a thorough investigation of the neutron contamination inherent in and about the primary x-ray beam of several medical therapy electron accelerators. Because of the small size of ECEPF dosimeters in comparison to other neutron meters, they have an unusually low perturbation of the radiation field under measurement. Due to this small size and the increased sensitivity of the ECEPF dosimeter over current techniques of measuring neutrons in a high photon field, the fast neutron contamination in the primary x-ray beam of all the investigated accelerators was measured with precision and found to be greater than that suggested by the other, more common, neutron dosimetry methods. This fast neutron dose component ranged from $\sim$ 0.2% (neutron dose equivalent per x-ray rad using $RBE_n = 10$) for the Clinac-20, 18 MV x-ray beam, to $\sim$ 1.3% of the x-ray dose in the BBC-45 betatron primary beam. We also found that fast neutron generation continued to increase between threshold and 45 MV rather trhan plateauing in the 20-25 MV region as other techniques have suggested. The thermal neutron dose measured by the ECEPF dosimeter was found to be approximately the same as that measured by other current techniques. During the course of our neutron investigations we also discovered a heretofore unreported (in medical therapy accelerators) heavy charged particle fluence in the primary x-ray beams generated by $\geq$ 25 MeV electron bombardment. This charged particle component is, in most cases,

15-20% of the fast neutron track density and has an average energy at the dosimeter (assuming certain conditions) of $\sim$4 MeV in the 25 MeV betatron x-ray beam. Our data suggests this charged particle component may be due to deuterons liberated by (γ,d) and (γ,np) interactions in the high Z accelerator components touched by the primary beam.

In a tangent field to the medical therapy accelerator research we have initiated an investigation into what may be a more important, albeit less controlable, area of photoneutron generation in high-energy x-ray therapy situations, viz. the human body as a neutron generator. Using a heterogeneous human phantom, our preliminary results at the bone-tissue interface show a fast neutron dose component which exceeds that found on the surface due to accelerator-produced photoneutron contamination. These fast neutron dose measurements range from $\sim$1.5% (neutron dose-equivalent per x-ray rad) in the 25 MeV beam treatment volume to $\sim$4% of the x-ray dose in the 45 MeV betatron treatment volume. Many more tests are called for in this area with emphasis on the neutron dose at different tumor depths, bone-tissue interfaces, and measurements both inside and outside the primary beam treatment volume for different beam cross sections.

Further advances were made concerning the phenomenon of two groups of tracks--one large and the other small--reported by Stillwagon (1978)[1] and questioned by Su (1979).[2] The resolution of this question is ultimately important to the health physicist because it concerns the mechanism of energy transfer or LET at the microscopic level. Our research has confirmed the existence of two distinct groupings of different diameter tracks. One set of tracks varies about a mean diameter of $\sim$ 50 microns and the other set about a mean diameter of $\sim$90 microns. Our experimental technique eliminated many of the scattering problems inherent, to varying

degrees, in both previous investigator's methods. These results were obtained using our standard electrochemical etching method consisting of an equal volume solution of 45% KOH and C_2H_5OH and etching at 1000 V, 2kHz, at room temperature for ninety minutes. Further tests are being planned which will utilize our casting technique, described in this report, to incorporate different amounts of C and O molecules into the polycarbonate to help finally resolve questions of energy transfer mode.

Our attempt to use the ECEPF dosimeter in conjunction with tablet radiators, albedo techniques and various filtering processes to measure the intermediate neutron energy dose has not been very satisfactory; i.e., while given improved results, it has not allowed us the accuracy we require in relation to known intermediate neutron fluences. In order to resolve this impass, our current direction of research in this area involves utilizing our polycarbonate casting method to incorporate the radiator (either ^{6}Li or ^{10}B) into the polymer. We are also investigating the use of plastics other than polycarbonate that, while not having some of the benefits of polycarbonate, have lower energy thresholds for track formation and can thus be used in conjunction with the ECEPF to help measure dose in the entire neutron energy range.

An adaptation of our thermal neutron dosimetry technique is being utilized to determine the ^{10}B content of blood examined after the injection of a ^{10}B-loaded compound into the patient. This research is related to the Boron Neutron Capture Therapy (BNCT) procedure under investigation at the Georgia Tech Research Reactor. At present, a calibration curve of ^{10}B concentration vs track density is being generated so that ^{10}B concentrations in blood and tissue samples can be determined in future clinical trials.

EXPERIMENTAL RESULTS

2. INVESTIGATION OF HIGH-ENERGY MEDICAL THERAPY ACCELERATORS

A primary tool in current cancer radiation therapy techniques is the high-energy x-ray beam generated in the betatron and linear accelerator. The bremsstrahlung x-rays from these medical accelerators are produced by impinging high-energy electrons upon metal targets. Fig. I gives a simplified illustration of the major components found in the primary beam of a typical accelerator. The components shown above the dashed line are found in the linac, and those located below the dashed line are common to both the linac and betatron.[3] These components are used either for the production of x-rays or shaping of the x-ray beam cross-sectional profile and are typically made of such elements as lead, tungsten, platinum, aluminum, copper, or gold, usually in combinations. Table I shows the composition of the accelerator components evaluated in this research.

At high x-ray energies ($>$ 6 MV) the threshold for photonuclear particle production is exceeded in most high Z elements as shown in Table II. Consequently, all of the components located in the primary beam shown in Fig. I must be considered as photoneutron, and to some extent charged particle generators. The dose delivered to the patient and operating personnel by the resultant particle fields, especially the neutron, is of concern to both the radiation therapist and the health physicist.

The majority of photoneutrons produced by photons in the energy range between neutron production thresholds and $\sim$ 30 MeV are a result of the "giant photonuclear resonance" cross section. Fig. II illustrates an example of this cross section. For high Z materials the photon energy for

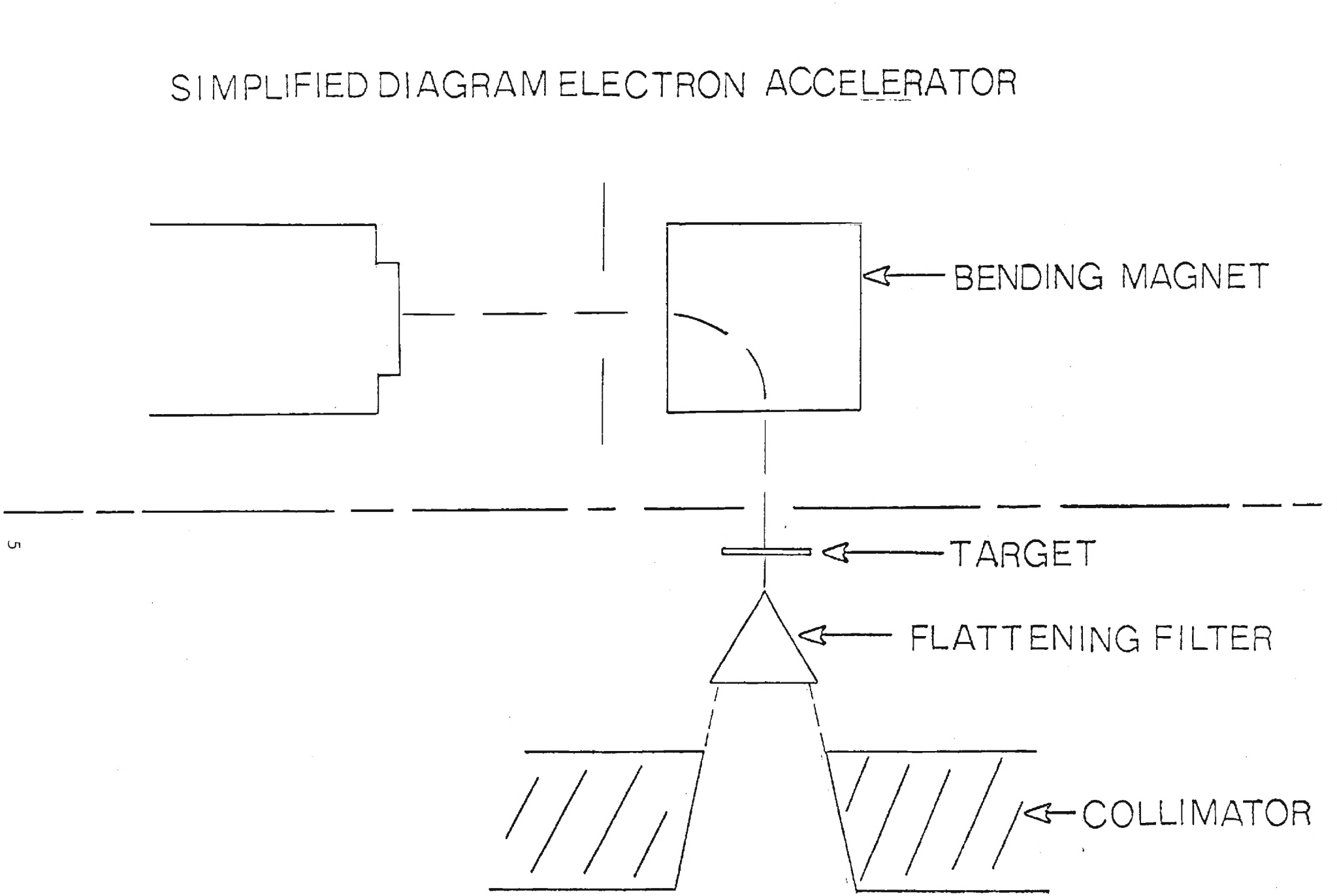

FIGURE-I SIMPLIFIED DIAGRAM ILLUSTRATING THE ACCELERATOR COMPONENTS EXPOSED TO THE PRIMARY BEAM. THOSE COMPONENTS LOCATED ABOVE THE DASHED LINE ARE FOUND IN THE LINAC AND THOSE LOCATED BELOW THE DASHED LINE ARE COMMON TO BOTH THE LINAC AND BETATRON.(3)

TABLE I

High Z Elements Found in Accelerators Investigated in this Research[3]

ACCELERATOR	ENERGY	COLLIMATOR	BEAM FILTER	TARGET	TARGET THICKNESS (mm)
Allis-Chalmers 25 MeV Betatron	25	Pb	Al	Pt	1.6
Brown-Boveri 45 MeV Betatron	45	W & Pb	Pb	Pt	2.0
Clinac-20	18				

TABLE II

High Z Elements Commonly Used in Accelerator Components and Some Parameters for Neutron Production by Giant Photonuclear Resonance[4]

ELEMENT	ATOMIC WEIGHT	ABUNDANCE (%)	(γ,n) THRESHOLD ENERGY (MeV)	σ max (mb)	ENERGY AT σ max (MeV)
Al	27	100.00	13.03	14	22.00
Cu	63	69.17	10.84	70	16.00
Cu	65	30.83	9.91	75	16.70
Cu	Nat.	-	9.91	70	17.00
W	186	28.40	5.75	400	14.00
W	Nat.	-	6.20	400	14.00
Pt	Nat.	-	6.10	500	13.90
Au	197	100.00	8.07	540	13.80
Pb	206	25.10	8.12	514	13.59
Pb	207	21.70	6.73	481	13.56
Pb	208	52.30	7.38	491	13.46
Pb	Nat.	-	6.73	-	-

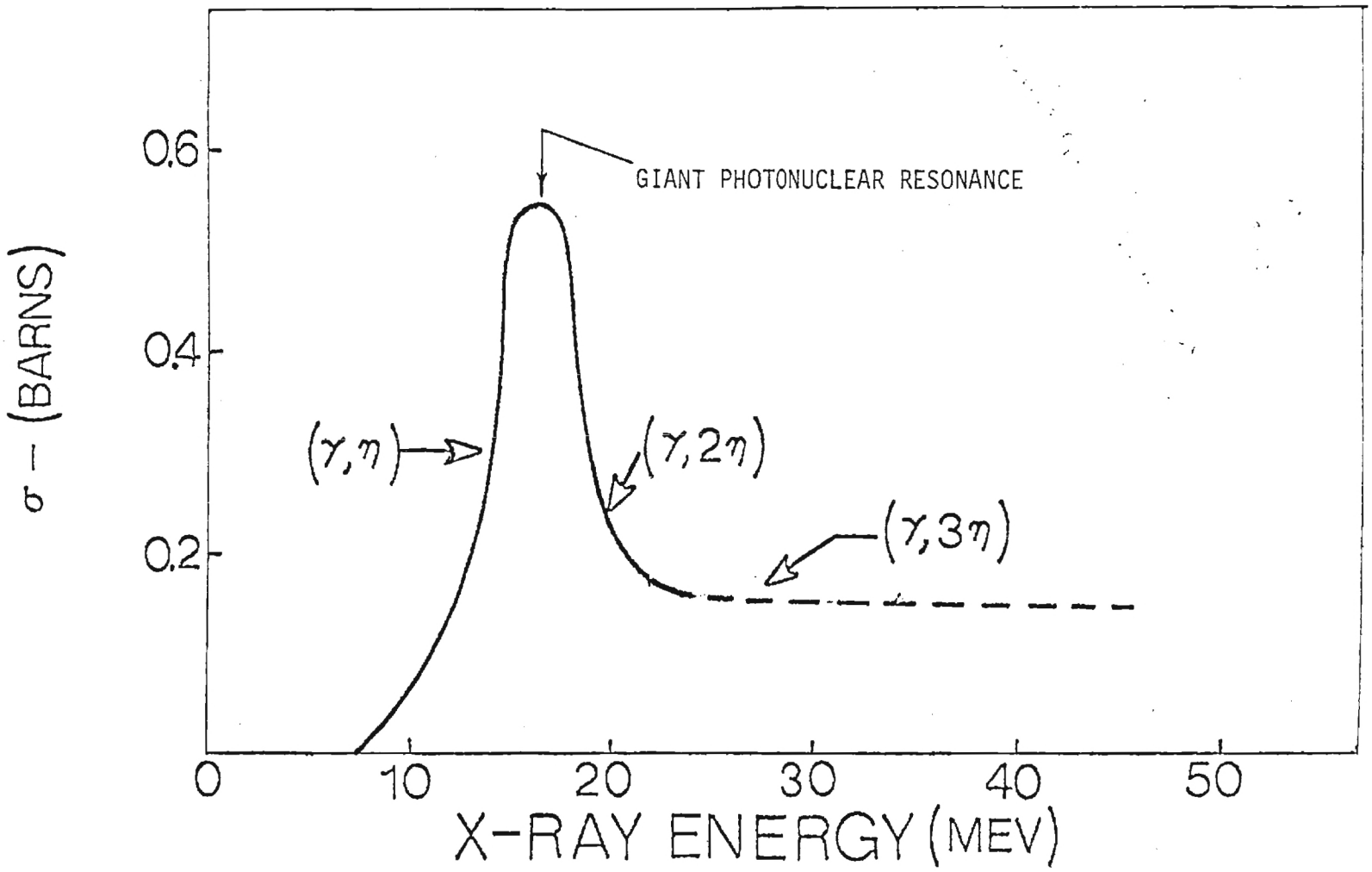

FIGURE-II TYPICAL GIANT PHOTONUCLEAR RESONANCE CROSS-SECTION AS A FUNCTION OF END POINT BREMSSTRAHLUNG ENERGY

the maximum giant resonance cross section is given approximately by $k_0 = 80A^{-1/3}$ MeV and varies between 13-18 MeV depending on the material.[4] The maximum cross section, σ max, is found from 3-6 MeV beyond the photoneutron production threshold and the peak full width at half maximum for heavy nuclei varies between 3-5 MeV. As can be seen in Fig. II, at higher photon energies beyond E max corresponding to σ max (γ, multiple n) interactions begin to predominate. The neutron energy spectra generated in the giant photonuclear resonance region results from neutrons produced by two distinct interaction processes: the "evaporation spectrum" and the "direct-emission spectrum".[5] The relationship of this giant resonance production to other neutron generation cross sections is shown as a function of photon energy for lead, up to and including the photopion cross section, in Fig. III. Fig. IV illustrates a typical photoneutron energy spectrum generated when the high Z target Ta is bombarded with high energy electrons. The neutrons in the Maxwellian shaped portion of the curve are generated by being evaporated from the compound nucleus formed as the energy from the photon is transferred by its electric field to the nucleus; thus causing an oscillation induction where the protons as a group move oppositely to the neutrons as a group.[6] This distribution of neutron energies, which resembles a fission-spectrum and has an approximately isotropic angular distribution of emission, accounts for 85-90% of the photoneutrons found in the primary x-ray beam. The average energies of the neutron spectra range from $\sim$ 1.3 MeV for the 18 MV x-ray beam of the Clinac-20 to $\sim$ 3 MeV for the BBC-45. As mentioned, this portion of the spectrum is adequately described by a Maxwellian distribution and can be given by:[7]

$$\frac{dN}{dE_n} = \frac{E_n}{T^2} \cdot \exp(-E_n/T) \qquad \text{(normalized to unit area)}$$

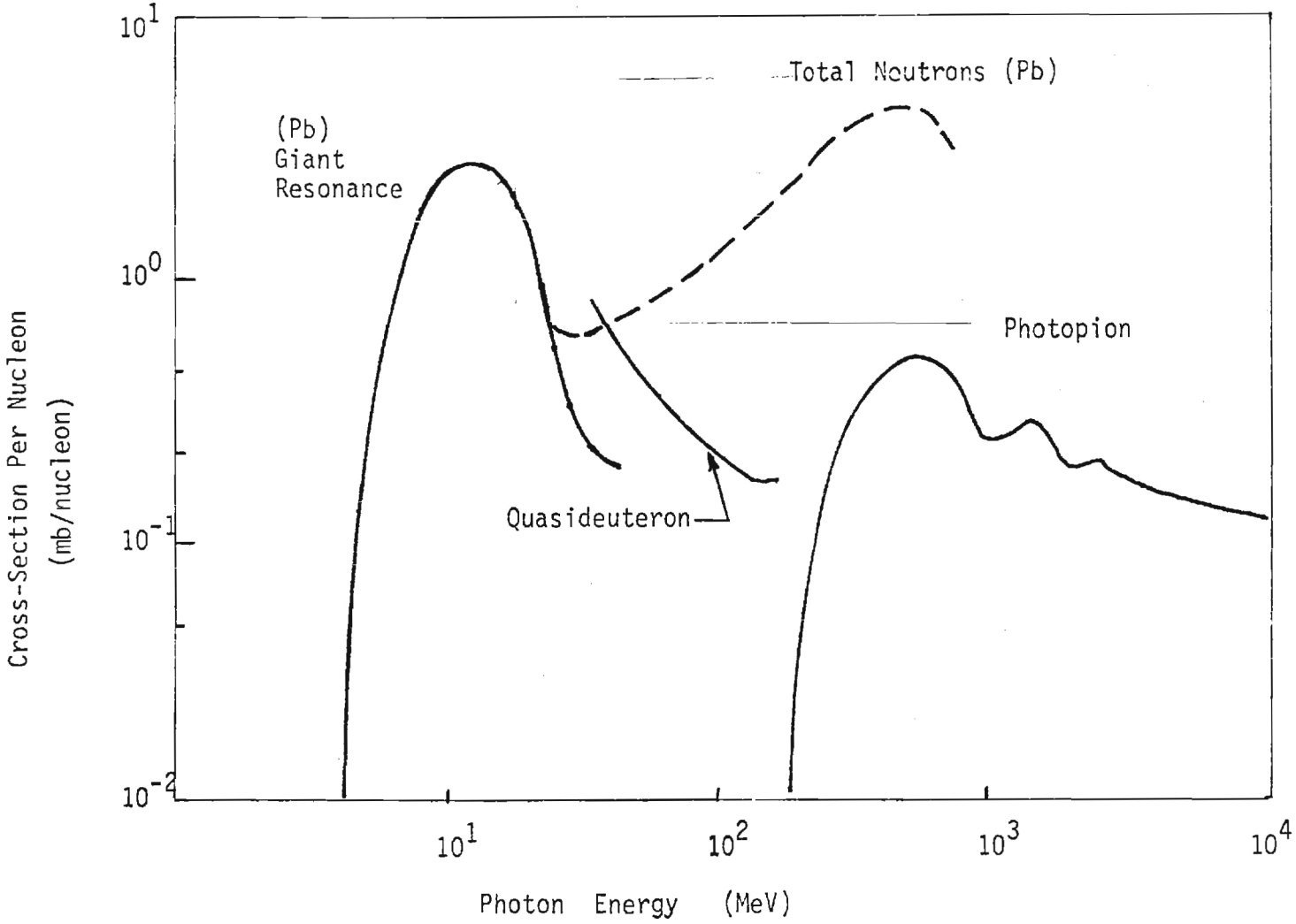

Figure-III Qualitative Comparison of Neutron-Producing Mechanism Cross-Sections as a Function of End-Point Bremsstrahlung Energy. From IAEA (4)

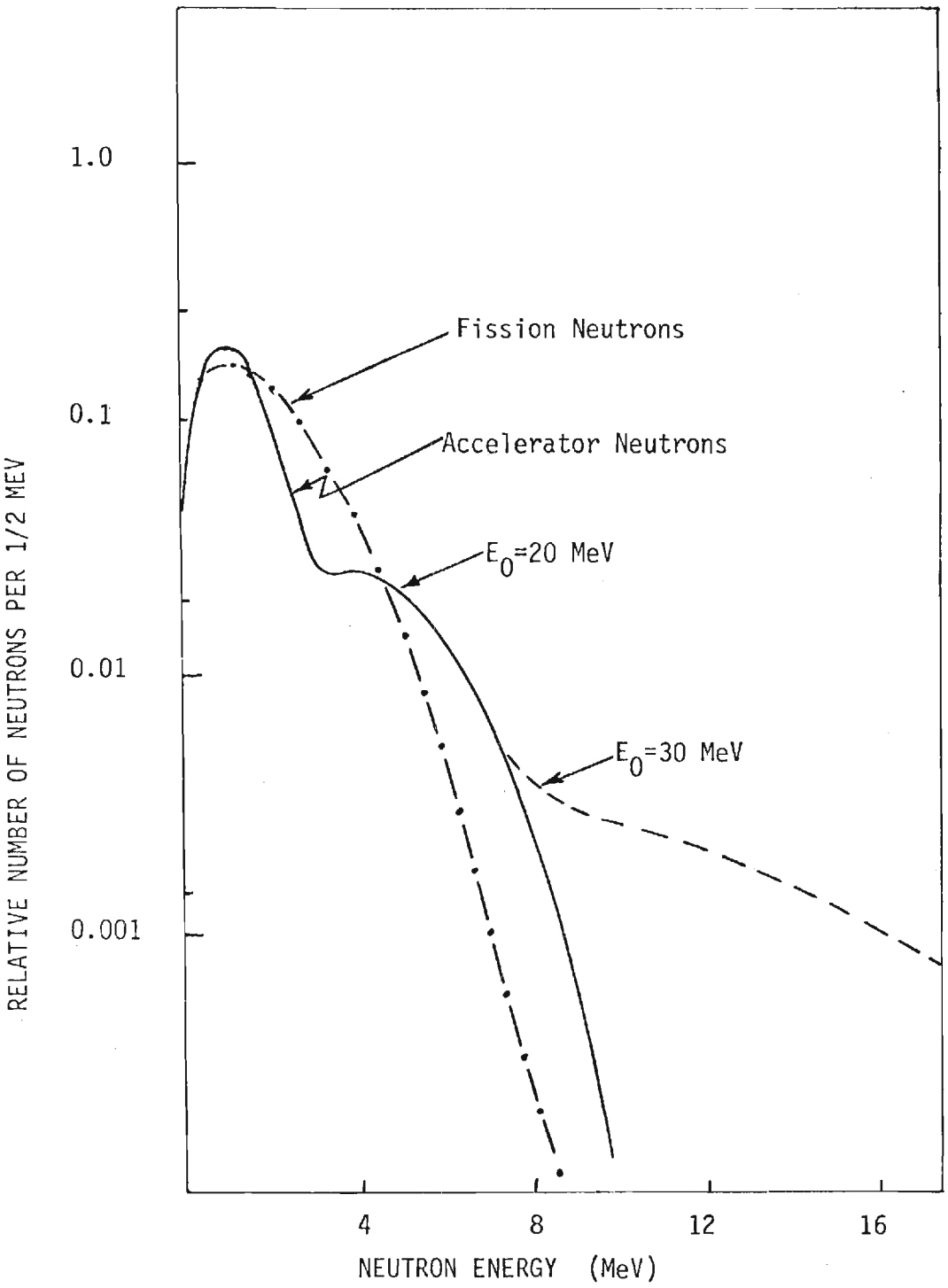

Figure-IV Accelerator Contamination Neutron Energy Spectrum Generated by Ta Target with Peak Bremsstrahlung Energies of 20 and 30 MeV, Compared to a Fission Spectrum. From NBS-97 (26)

where, T = the nuclear temperature (in units of MeV), characteristic of the target nucleus and its excitation energy. From this we see that the spectrum will peak at a most probable energy of $\hat{E}_n = T$ and that the average energy is $\bar{E}_n = 2T$.[7] The remaining 10-15% of photoneutrons, responsible for the "bumps" in the spectral curve shown in Fig. IV, are found in the high-energy tail attached to the fission-like spectrum. These neutrons are produced by the direct-emission or "photoionization" process in which a neutron (or n-p pair) in the nucleus receives all of an interacting photon's energy and is ejected at that energy minus the binding energy of the neutron to its nucleus. These directly emitted photoneutrons exhibit an angular distribution that is slightly peaked at 90° to the direction of the incident photon. Theoretically, this portion of the spectra could contain neutrons with an energy only a few MeV less than the end point maximum of the bremsstrahlung therapy beam. In practice, however, we do not expect any significant contribution from the neutrons above $\sim$ 20 MeV even in the 45 MeV betatron beam.

The dosimeter used in this study is based on electrochemical etching of particle tracks in low background ($\sim$ 2 tracks/cm^2) polycarbonate foils. The fast ($>$ 1.1 MeV) neutron dose is a function of the number of recoil particle tracks produced primarily by recoil oxygen and carbon nuclei and alpha particles from (n,α) reactions with atomic constituents of the polycarbonate. The thermal neutron dose component is measured by using specially designed ^{6}LiF radiator tablets in conjunction with the polycarbonate foils and measuring the reaction particle track density as a result of alphas and tritons from the $^6Li(n,\alpha)^3H$ thermal neutron reaction. The charged particle dose is determined from the direct density of damage tracks formed in the polycarbonate.

As the recoil reaction or direct charged particle traverses the polycarbonate, damage regions are left behind around their trajectories. These regions are preferentially etched by the electrochemical etching sufficiently to be seen by the unaided eye and evaluated with low ($\sim$ 100X) magnification. The electrochemical etching of polycarbonate foil, ECEPF, dosimeter has been shown to have a dose-equivalent or rem response (as seen in Fig. V) over a wide neutron energy range once the threshold energy for track formation has been exceeded.[1,2,23]

In this study, multi-layer packets of 250-micron thick Transilwrap polycarbonate foil layers were exposed to 500-2000 rads of high-energy x-rays, measured at the maximum dose point and typical TSD's, in the center of a 10 cm x 10 cm primary beam of a Varian Clinac-20 (18 MV x-ray beam), an Allis-Chalmers 25 MeV betatron and a Brown-Boveri 45 MeV betatron in both the 45 and 33 MV x-ray modes. The ECEPF dosimeter was irradiated in each accelerator beam with care taken to insure no significant neutron reflection was apparent from the treatment table, floor, etc. After exposure, the polycarbonate foils were electrochemically etched in an equal volume solution of C_2H_5OH and 45% KOH at 1000 V and 2 kHz for ninety minutes at room temperature.

Charged Particle Measurement

Fig. VI exhibits the polycarbonate dosimeter response as a function of the individual 250-micron thick foil layers in the multi-layer stacks exposed to the primary x-ray beam in each of the investigated accelerators. As can be seen, the response with increasing layer depth is relatively uniform with the 18 MV linear accelerator, suggesting only the fast neutron dose is being measured. Notice, however, the dosimeter repsonse in its initial layers when exposed to the 25 MV x-ray beam and the even more

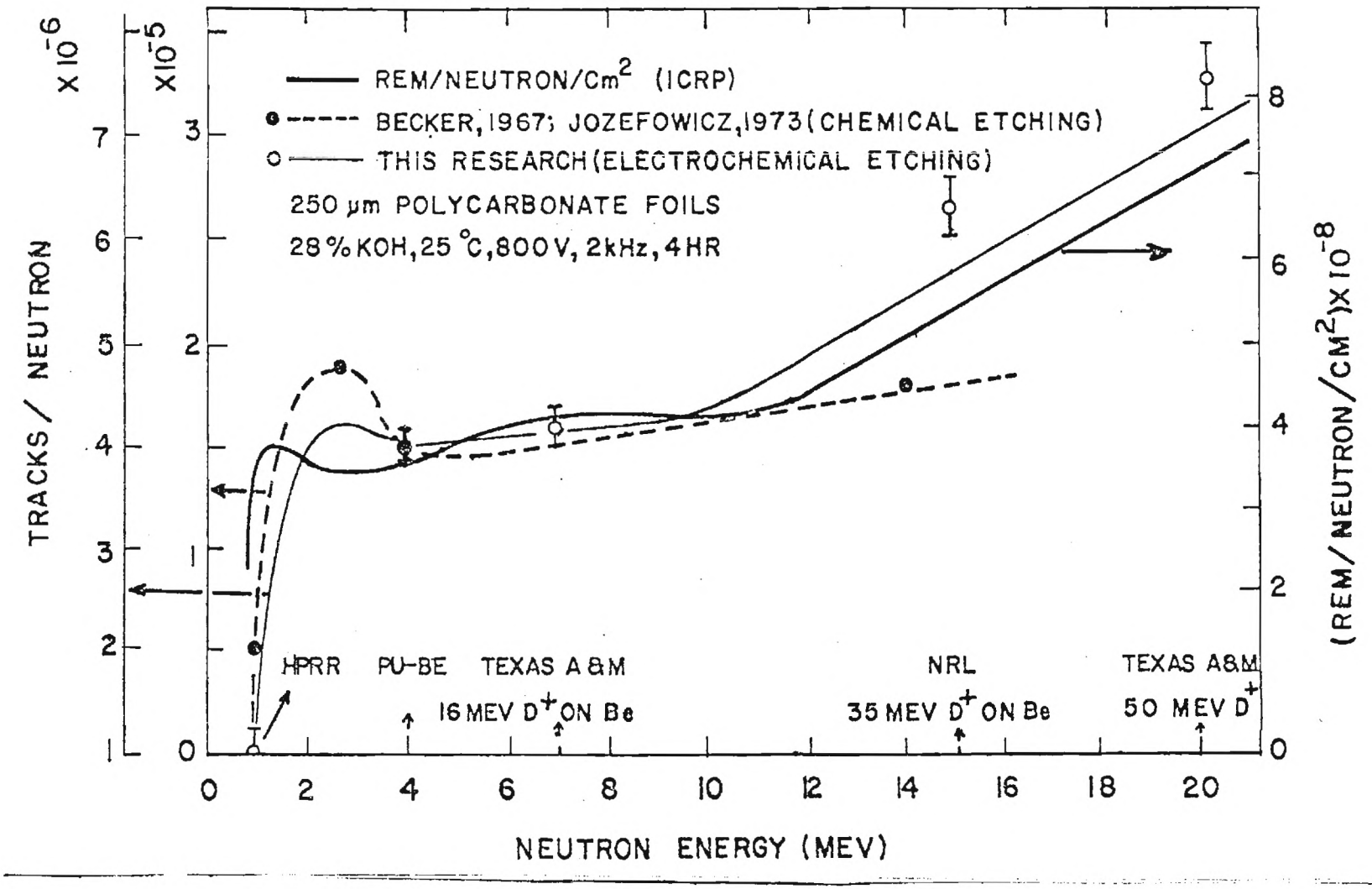

Figure-V Neutron Sensitivity (tracks/n) as a Function of Neutron Energy. Obtained by Sohrabi Using Electrochemically Etched 250 micron Polycarbonate Foils. These Data are Superimposed on Conventional Etching Data and Compared to the ICRP Rem Curve. From Sohrabi(23), Jozefowicz(24), and Becker(25).

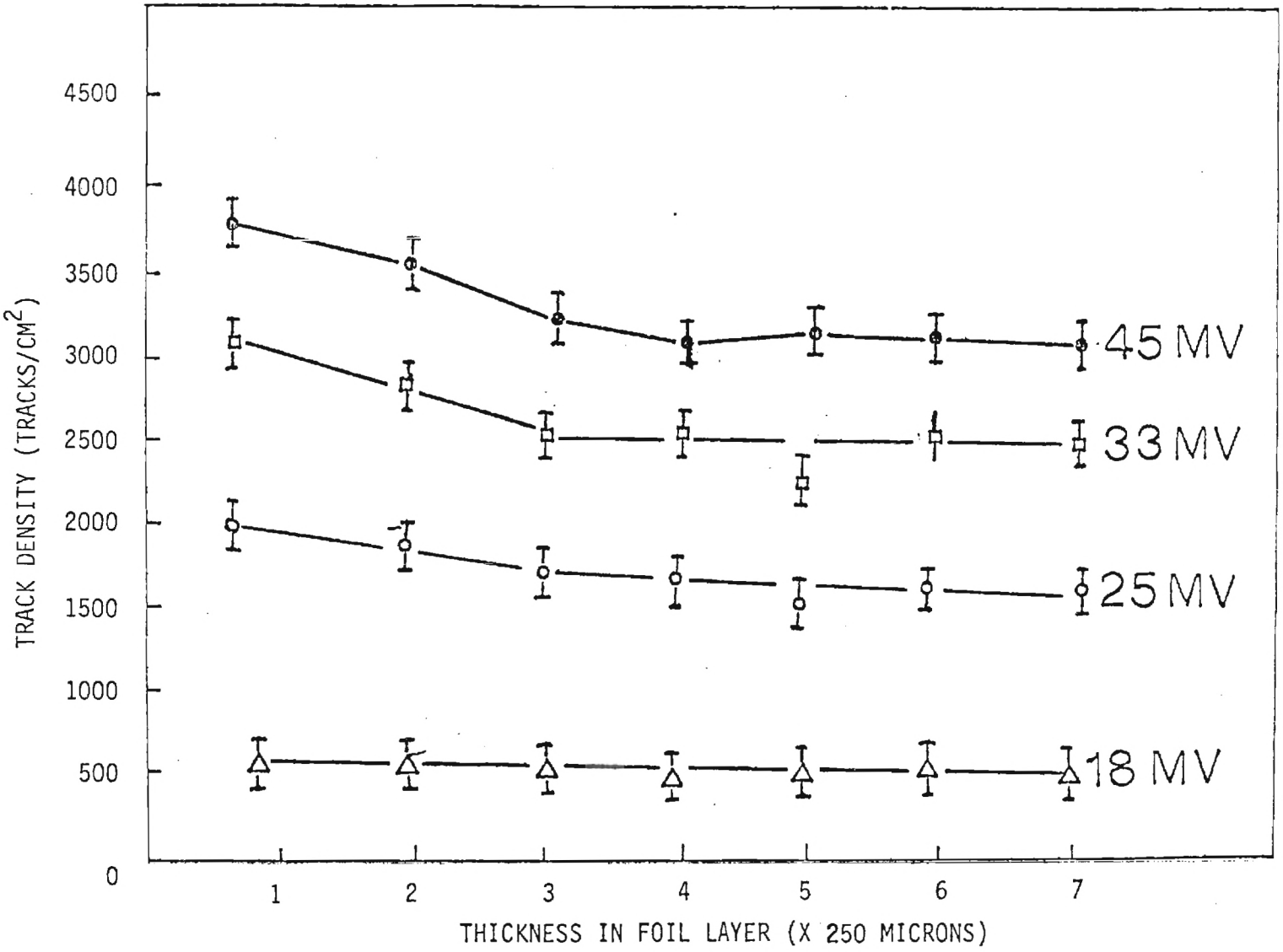

FIGURE-VI POLYCARBONATE FOIL RESPONSE AS A FUNCTION OF 250 MICRON LAYERS WHEN EXPOSED TO THE PRIMARY X-RAY BEAM OF SEVERAL MEDICAL THERAPY ACCELERATORS.

pronounced effect in the initial layers in the 33 MV and 45 MV beams. Here the data exhibits a track density of, in some cases, 15-20% higher in the first layers before leveling off and remaining relatively stable throughout successive layers (up to fourteen 250-micron thick layers were evaluated in the BBC-45 MV studies). The results of a subsequent series of tests evaluating the effect of different thicknesses of thin (40 micron) polyethelene absorbers on this fluence can be seen in Fig. VII.

If we assume this measured phenomenon is due to a charged particle component, the most likely candidates are protons, alphas, or deuterons. While we know that protons are liberated from the high Z nucleus in much the same fashion as neutrons[5] (although at lower fluences due to the more rigorous escape ordeal), tests to date have failed to show that the polycarbonate dosimeter can measure the proton track unless specially treated with U.V. light.[8] Both theoretical and experimental evaluations of the alpha particle generation in the energy range of medical therapy accelerators suggest that any alpha track densities (tracks/cm^2) produced will have less than one thousandth the track density of the photoneutrons.[4,5,6] During the high energy (> 25 MeV) direct-emission process there is the possibility of not only measurable neutron and proton generation but also the possiblity of deuteron (or n-p pair) production. Since the separation energy for deuteron emission from the high Z nucleus is in most cases quite high (e.g., 15 MeV for Cu) and the penetrability of the Coulombic barrier quite rigorous, deuteron emission is often considered insignificant at the medical therapy beam energies in question. However, scant empirical measurements have suggested this deuteron component to be in some cases as much as $\sim$10% of the measured neutron fluence in x-ray beams produced by high-energy electron bombardment of metal

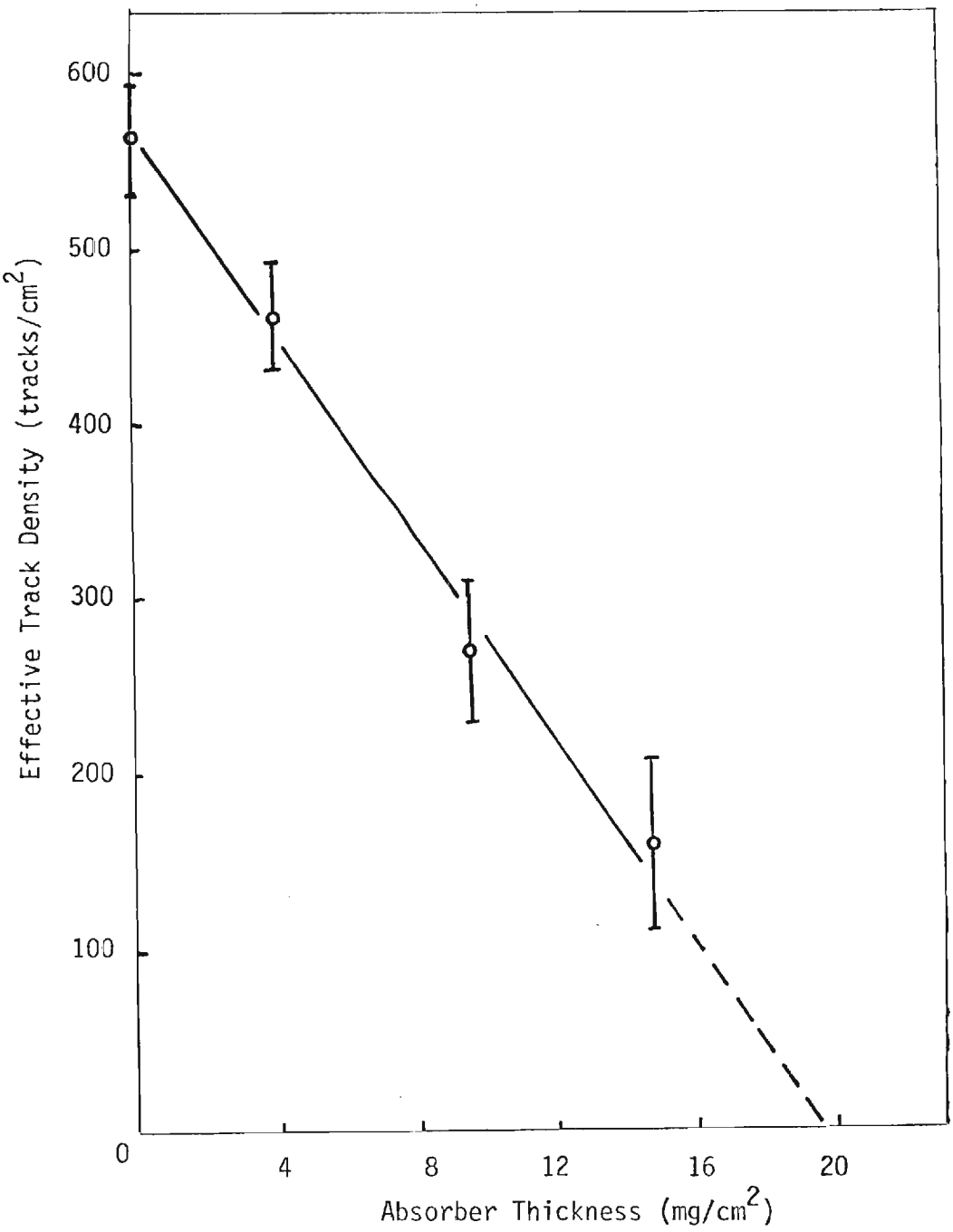

Figure-VII Range Determination of Charged Particle Found in 25 MeV Betatron X-ray Beam. Track Density in Polycarbonate Foil as a Function of Absorber Thickness in Air (Calculated from Thin Polyethelene Absorbers).

targets.[9,10,11] A possible explanation for this higher than predicted yield of photodeuterons is that the directly emitted photoneutron or photoproton may pick up another nucleon while escaping from the nucleus.[5] With this "pick-up" process in mind, statistical models have been generated which afford an order of magnitude agreement with experimental results.[12]

With the above in mind and comparing the range curves for alphas, protons and deuterons as illustrated in Fig. VIII with our experimental determinations of the range of the observed charged particle fluence from Fig. VII, we see that the most likely composition of this fluence incident on the dosimeter is $\sim$4 MeV deuterons. However, since no evidence has been uncovered that documents the ability of the ECEPF technique to measure deuterons, further testing utilizing "clean" deuteron beams of various energies is called for.

Thermal Neutron Measurements

Fig. IX shows a comparison between the thermal neutron dose measurements made using the ECEPF dosimeter and one of the more prevalent techniques currently used in medical therapy accelerators, indium foil activation using a water moderator. The figures are in thermal neutron dose per x-ray rad and exhibit relatively close agreement for both the 25 and 45 MeV betatron, considering the very small doses measured ($\sim 1\frac{1}{2}$ mrem with the ECEPF dosimeter).

Thermal neutron dose measurements were also conducted with the ECEPF technique at various locations inside the patient treatment room, at the operator console, and at other adjacent work areas during a typical patient treatment use of the 25 MeV accelerator at Emory University Winslip Clinic, Atlanta, Georgia. Fig. X gives both a sketch of the measured area and the

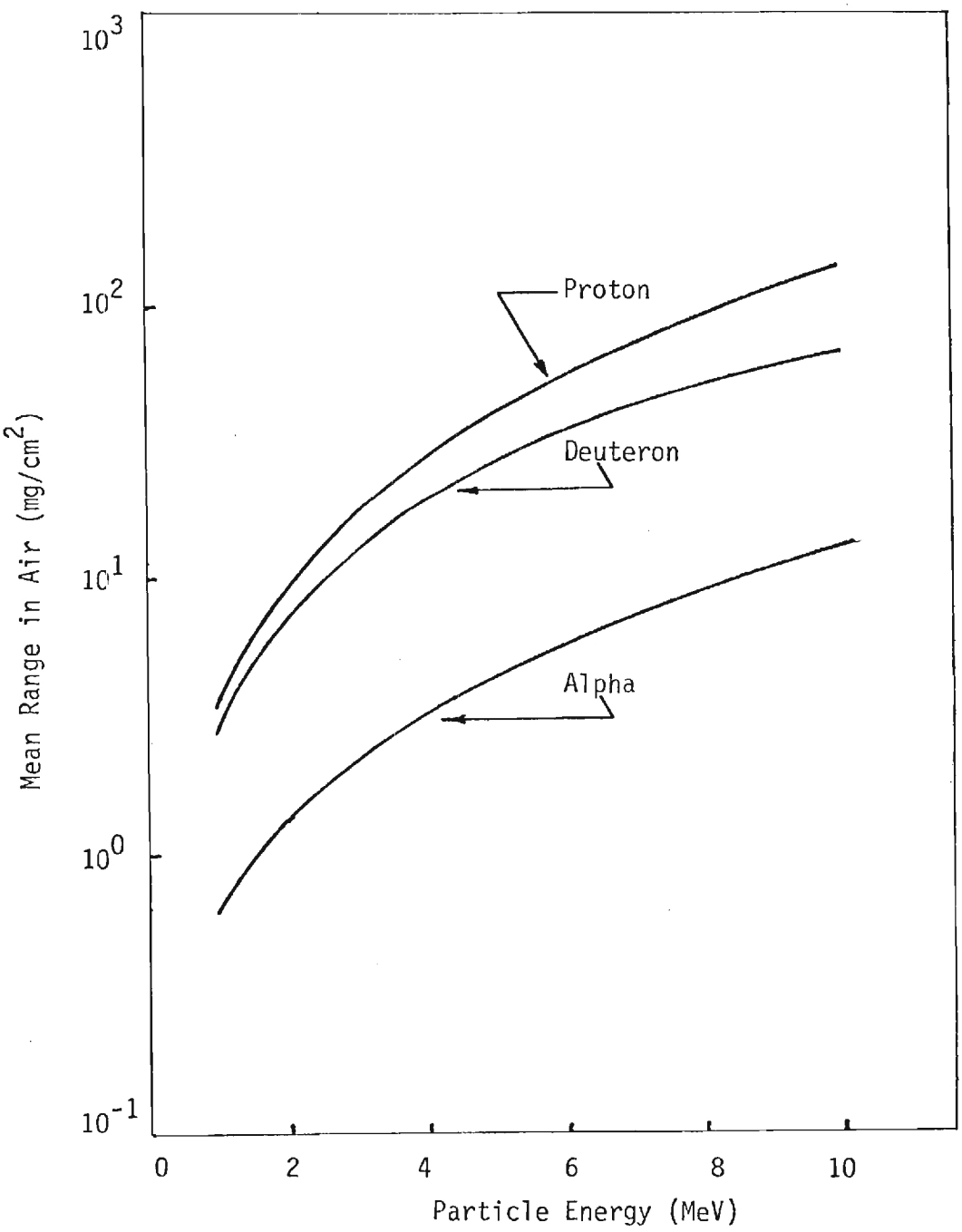

Figure-VIII Mean Range (mg/cm^2) in Air of Protons, Deuterons, and Alpha Particles as a Function of Energy. Adapted from Lapp and Andrews (31) and Morgan and Turner (32).

ACCELERATOR	SLOW NEUTRON DOSE PER RAD X-RAY	
	IN + H_2O MOD.	^6Li-ECEOPF —
A-C 25	4.3×10^{-6}	1.4×10^{-6}
BBC-45	2.9×10^{-6}	1.4×10^{-6}

FIGURE-IX THE ELECTROCHEMICAL ETCHING OF POLYCARBONATE FOIL (ECEPF) MEASUREMENT OF THE THERMAL NEUTRON DOSE EQIVALENT PER X-RAY (RAD) FOR TWO HIGH ENERGY MEDICAL ACCELERATORS, COMPARED TO THE MOST COMMON TECHNIQUE NOW IN USE FOR MEASUREMENT OF THERMAL NEUTRONS IN HIGH PHOTON FIELDS.

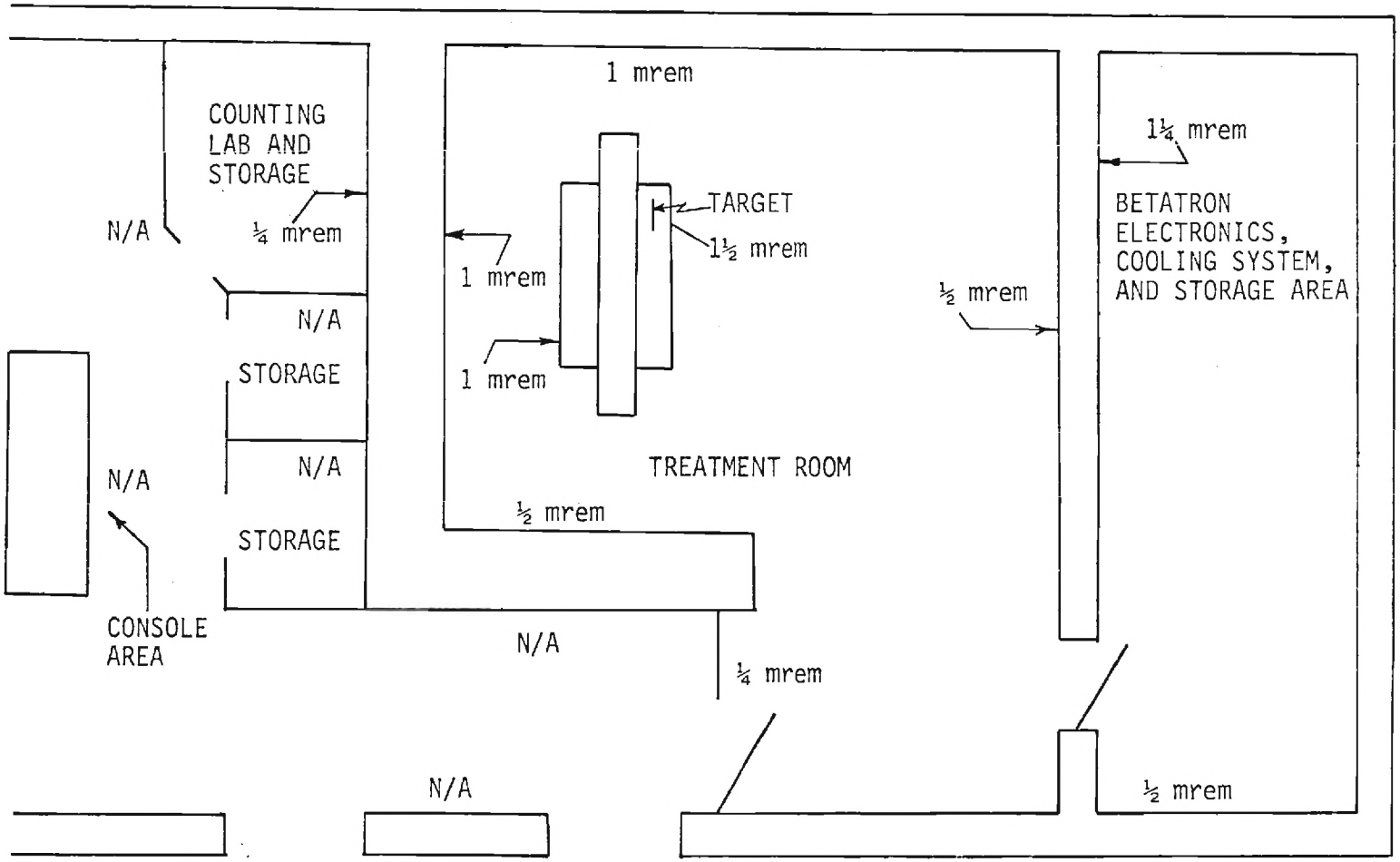

FIGURE-X THERMAL NEUTRON AREA DOSIMETRY OF THE 25 MEV ALLIS-CHALMERS TREATMENT ROOM AT EMORY UNIVERSITY WINSLIP CLINIC, ATLANTA GEORGIA. THE ECEPF+LiF THERMAL NEUTRON DOSIMETER WAS USED FOR THESE MEASUREMENTS. (These measurements were taken for a time = ~20 min.)

thermal neutron doses recorded at particular locations. As one would expect, a fairly uniform thermal neutron dose existed in the treatment room due to the thermalizing properties of the concrete floor and walls. The measurements at the operator console were negligible.

Fast Neutron Measurements

Fig. XI exhibits a comparison between the fast neutron dose equivalent per x-ray rad determined by the ECEPF dosimeter and a cross section of other current methods of measuring fast neutron contamination in medical therapy x-ray beams. As can be seen the ECEPF technique suggests that the fast neutron dose is considerably larger than previous, less sensitive measurement techniques have exhibited. Fig. XII shows graphically a similar comparison to Fig. XI. Here we note that conventional methods of measuring the fast neutron contamination in x-ray beams exhibit a plateau, or at least considerably smaller values, in the 20-25 MV range; this would be consistant with expected fast neutron yields only if we were bombarding a thin (i.e., ≤ 1 radiation length thick) target with high-energy electrons. This can be understood from Fig. XIII, which shows the increasing photoneutron generation as a function of increasing target thickness and of bombarding primary electron energy (which, of course, is directly related to the maximum x-ray energy). As the thickness of the target under electron bombardment increases to greater than one radiation length (X_o in the graph) the photoneutron generation no longer plateaus around the 20-25 MeV range, as it tends to do at one radiation length or less target thickness. Instead it continues to increase as the primary electron energy increases. As shown earlier in Fig. I, we must consider not only the target but all else in the primary x-ray beam as a photoneutron generator. The ECEPF dosimeter data suggests that if we consider the target, main

THERAPY MACHINE	MEASUREMENT TECHNIQUE			
	IN + H_2O MODERATOR (a)	IN + PARAFIN MODERATOR (a)	P_2O_5 ACT. (a)	ECEOPF (a)
CLINAC-20	—	—	—	0.2
AC-25	0.51	0.45	0.28	0.76
BBC-33	—	—	—	1.04
BBC-45	0.54	0.39	0.73	1.18

(a) = % N_F - DOSE EQUIVALENT PER X-RAY DOSE - RAD

FIGURE-XI THE FAST NEUTRON PERCENT DOSE EQUIVALENT PER X-RAY (RAD) AS MEASURED IN THE PRIMARY BEAM BY THE ELECTROCHEMICAL ETCHING OF POLYCARBONATE FOIL TECHNIQUE, COMPARED TO OTHER COMMON MEASUREMENT METHODS.(3)

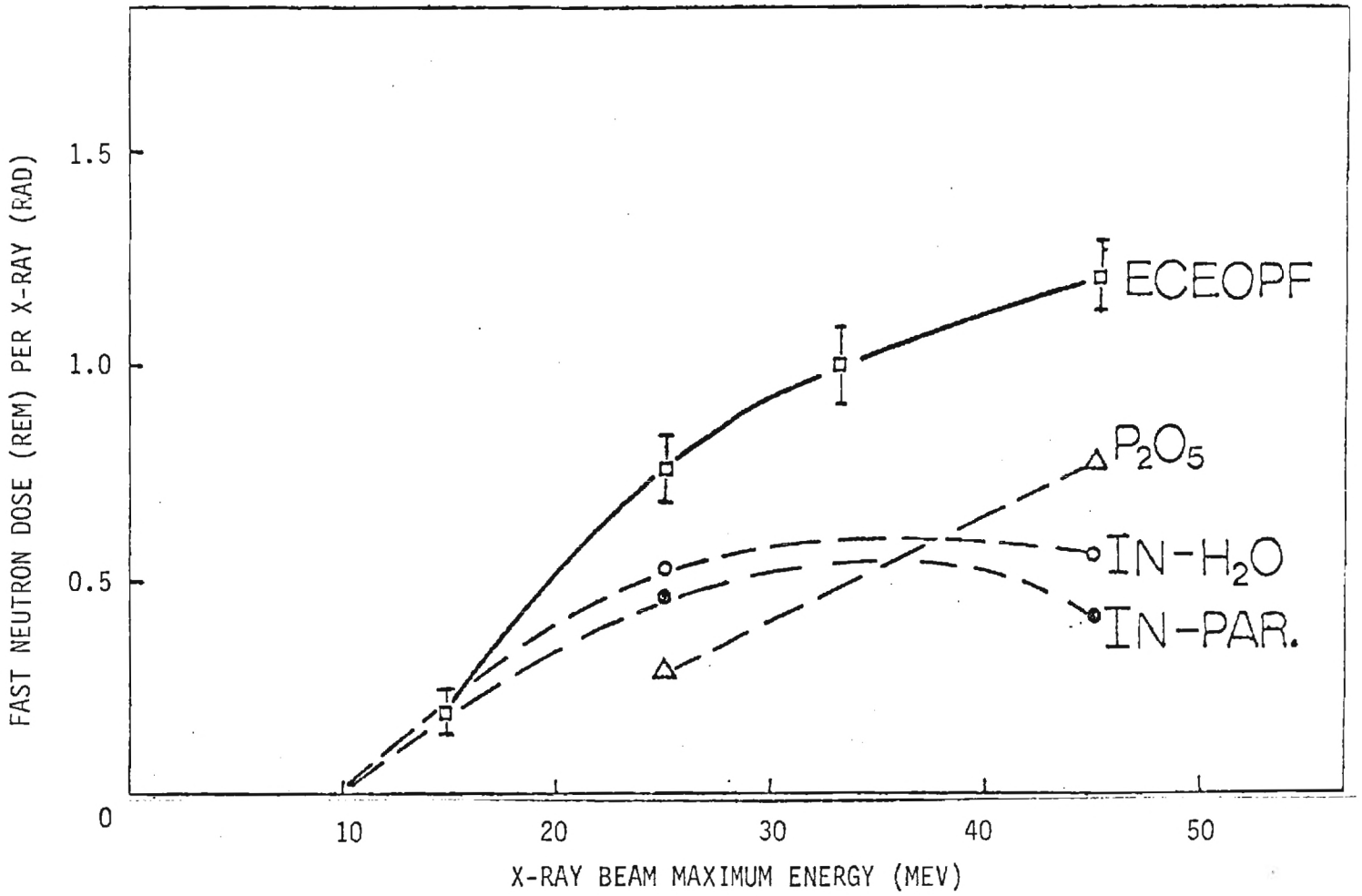

FIGURE-XII GRAPHICAL COMPARISON OF FIG.-XI. THE ECEPF DOSIMETER RESPONSE TO FAST NEUTRONS IN THE PRIMARY BEAM OF SEVERAL HIGH ENERGY MEDICAL THERAPY ACCELERATORS, COMPARED TO OTHER NEUTRON MEASUREMENT METHODS.

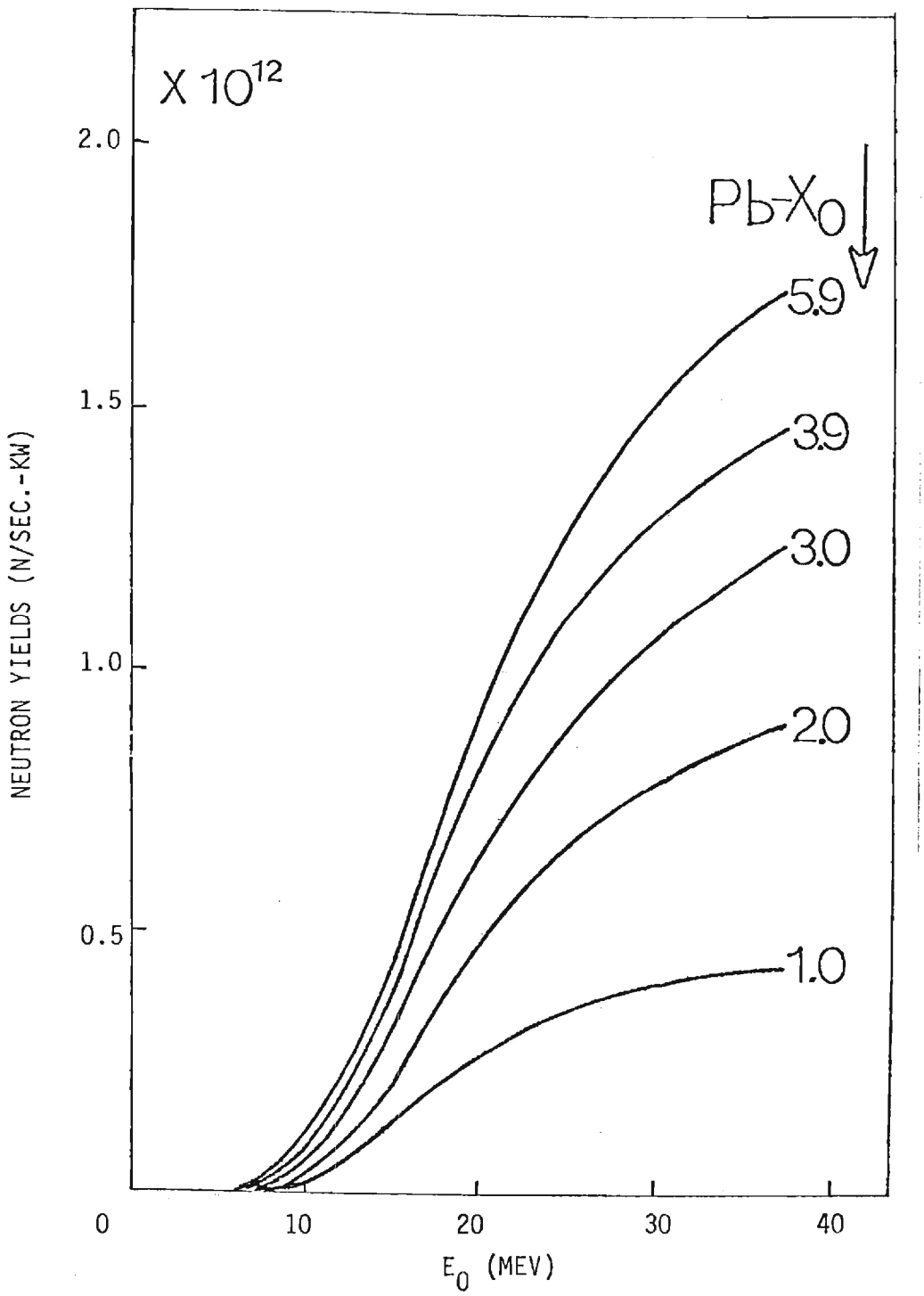

FIGURE-XIII NEUTRON YIELDS FROM ELECTRONS INCIDENT ON A LEAD TARGET OF VARIOUS THICKNESSES. ADAPTED FROM (4)

collimator, and flattening filter as significant neutron generators (as the literature suggests,[3,7] and our further testing has confirmed), we do indeed approach a "thick" target situation and find the photoneutron production to increase between threshold and 45 MeV rather than plateauing in the 20-25 MeV range as data from other less sensitive techniques have suggested.

To determine the ECEPF dosimeter response to the photoneutrons generated by the various accelerator components (as illustrated in Fig. I) and at the same time determine the individual contribution of each component, the following test was performed. The dosimeter was exposed to 1000 rads of x-rays in the standard testing configuration (the same as our other fast neutron evaluations) except in each test one of the accelerator components was either physically removed from the primary beam (as with the flattening filter) or adjusted to give an indication of contribtuion (e.g., the lower collimation jaws were evaluated at a closed position, 10 x 10 cm, and 30 x 30 cm while using a 10 x 10 cm dosimeter foil). From this data the main photoneutron generators in a typical patient treatment set-up were the target plus main collimator (78%) and the falttening filter (20%). This study was performed on the BBC-45 MeV betatron only, and the findings are consistant with those in the literature.[3,7]

3. NEUTRON GENERATION IN A HETEROGENEOUS HUMAN PHANTOM

The photoneutrons generated inside the human body during high-energy radiotherapy treatments differ significantly from those produced by the accelerator components. While the magnitude of accelerator produced photoneutrons is generally controlable (e.g., use of different Z materials, neutron shielding, etc.) the neutrons produced by high-energy photon interactions with the body are an unavoidable situation in accelerator radiotherapy. Also, unlike the accelerator produced neutrons which are predominantly found within the primary x-ray beam, the neutrons produced by the human body are found to varying extents, depending on the treatment field size, both inside and outside the treatment volume. Thus, for these reasons and since neutrons have a much different depth dose dropoff compared to x-rays as illustrated in Fig. XIV and Fig. XV, it is important that the medical physicist knows the extent and magnitude of these parameters for various treatment situations so that the optimum effective treatment plan can be formulated.

Our research in this area utilizes a heterogeneous human phantom consisting of a 30 cm diameter x 45 cm high cylinder (0.5 cm thick polyethelene wall) filled with Goodman's tissue-equivalent liquid[13] in which was placed a 4 cm diameter x 33 cm high cylinder (0.3 cm thick polyethelene wall) containing a bone-equivalent liquid.[14] The elemental composition of these equivalents compared to those of reference man can be seen in Table III. Also shown in Table III are the thresholds for neutron generation and maximum cross sections for each element which appreciably contributes to the photoneutron fluence. In this study to date, neutron dose data has been measured at the bone-tissue interface, both anterior and

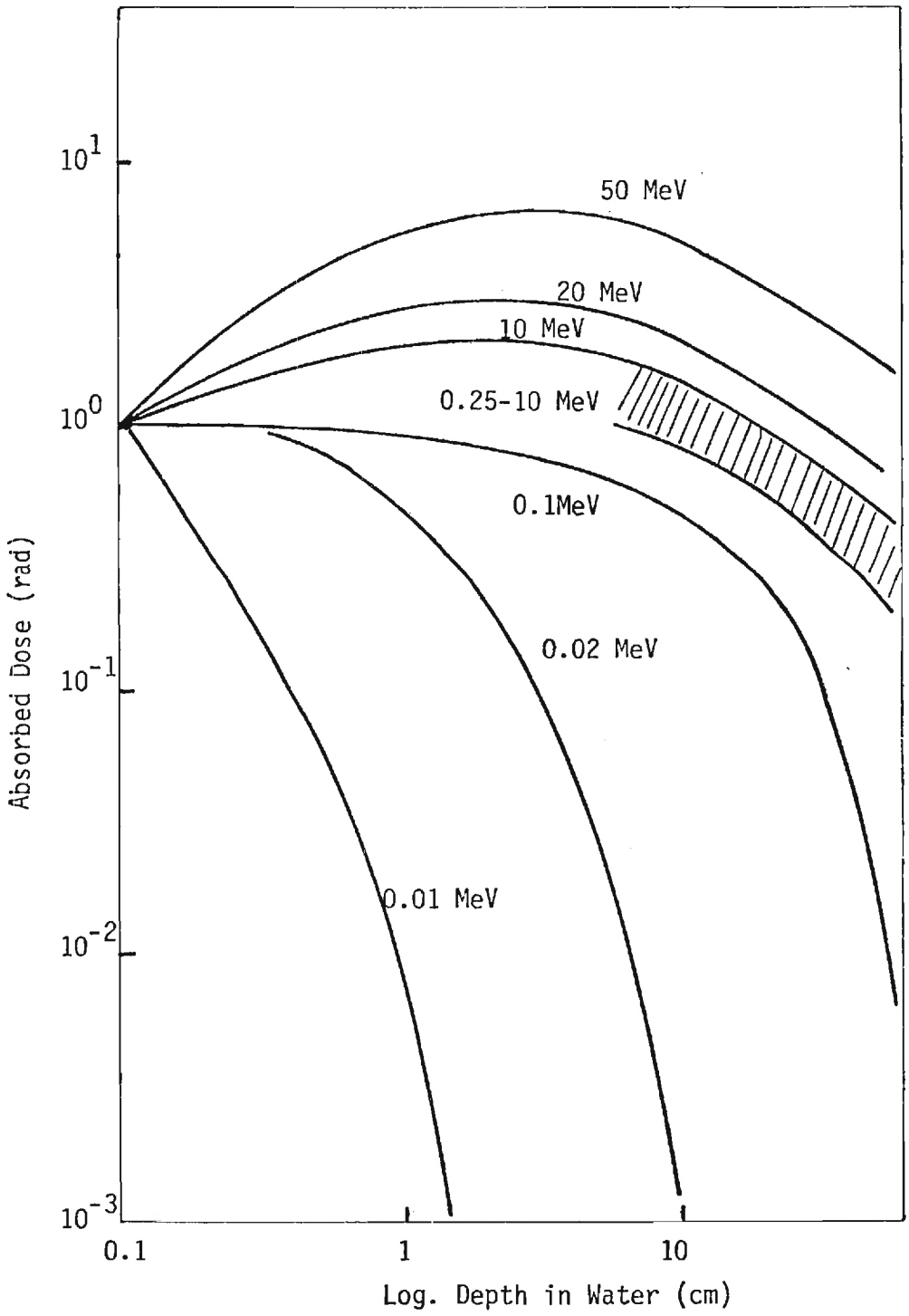

Figure-XIV Absorbed Dose Per Unit Surface Dose (rad) as a Function of Depth in Water, Calculated for Different Photon Energies. From Becker (27) After Joffre (28)

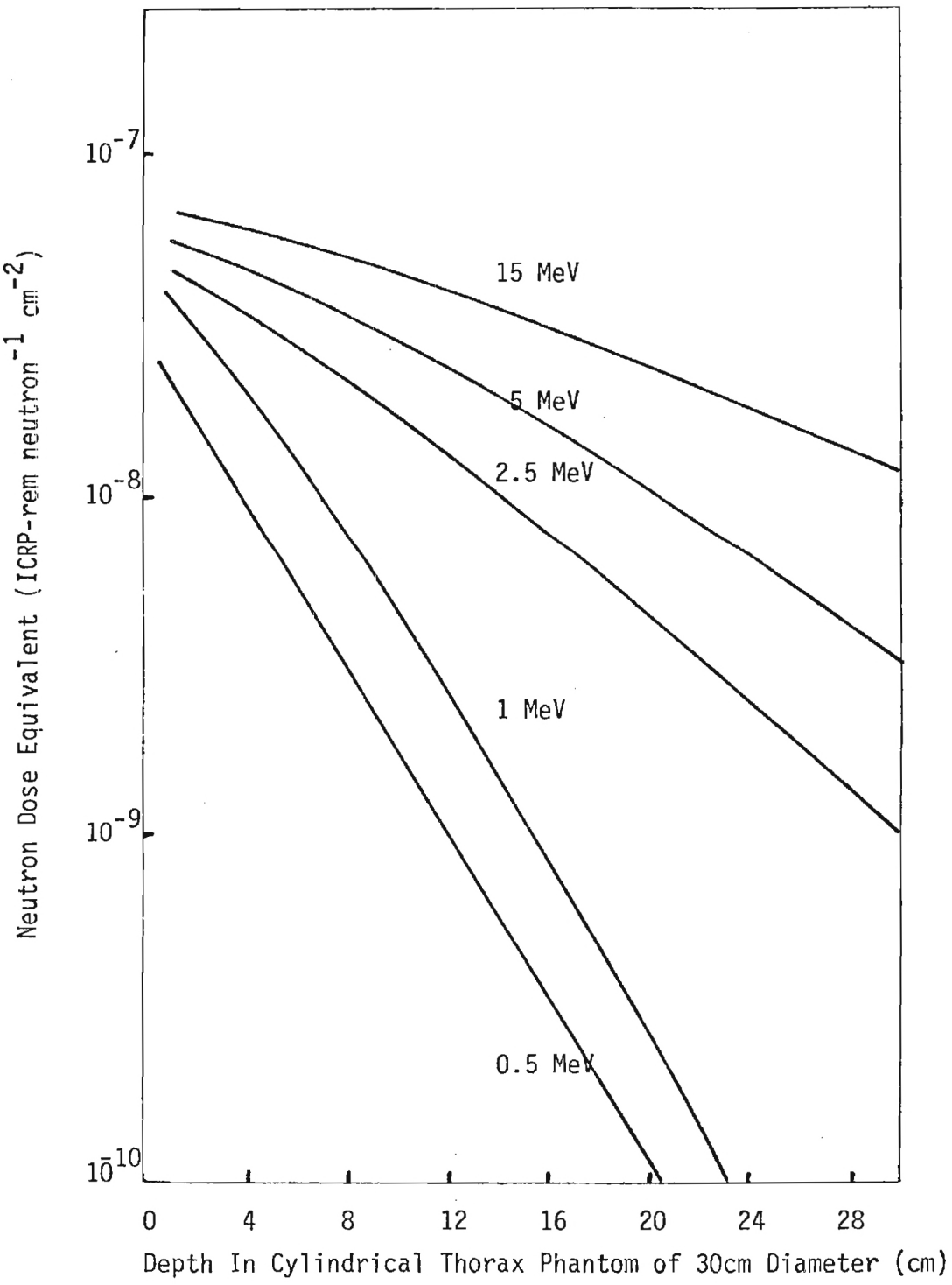

Figure-XV Calculated Dose Equivalent (rem) as a Function of Depth in a Phantom for Different Energies. From Becker (27) After Auxier (29)

TABLE III

Elemental Composition (% by weight) of Heterogeneous Phantom in this Research Compared to Reference Man (33), also a Listing of the Photoneutron Thresholds and Maximum Cross Sections for the Major Contributing Elements [4]

ELEMENT	REFERENCE MAN		BONE EQUIVALENT LIQUID (14)	TISSUE EQUIVALENT LIQUID (13)	PHOTONEUTRON	
	SKELETON	TISSUE*			THRESHOLD (MeV)	σ_{max} (mb)
H	7.0	10.2	6.5	10.2	-	-
C	22.7	12.3	19.1	12.0	18.72	7
N	3.9	3.5	3.9	3.6	10.55	15
O	48.6	72.9	53.0	74.2	15.67	8
Na	0.3		0.2		~ 13	~ 8
Mg	0.1		0.2		~ 16.5	~ 9
P	7.0		6.8		~ 13	21
Ca	9.9		10.3		15.63	17
S	0.2		-		~ 15	11
Cl	0.1		-		~ 10.5	28
K	0.2		-		~ 13.5	24

* S + K + P + Na + Mg = 1.1%

posterior to the primary x-ray beam, for a typical radiotherapy treatment set-up in the 25 MeV betatron beam and the 33 and 45 MV beam modes of the 45 MeV betatron. Fig. XVI exhibits the neutron dose-equivalent per x-ray rad (as determined at the dosimeter depth) increase as a function of maximum x-ray energy of the primary beam. For this preliminary test, the treatment depth (to the bone-tissue interface) was 10 cm and the delivered x-ray dose was $\sim$1000 rad for each accelerator. As can be seen in Fig. XVI, the neutron dose increases appreciably between the 25 and 33 MV beams (1.5% to 3.21%) and then increases at a somewhat slower rate between the 33 and 45 MV beams (3.2% to 4%). While the magnitude of neutron dose is hard to compare with theory (because of the wide variation depending on treatment set-up, depth dose, phantom composition, etc.), this is fairly consistent with the literature which predicts a large neutron fluence increase between 20 and 30 MeV with a more gradual increase above 30 MeV.[15]

Current tests are underway to evaluate the neutron dose at various depths in the phantom for tissue only and at all positions on the bone-tissue interface. A myriad of tests are planned for this study in the future, some of which include the use of polymers with lower thresholds for track formation (e.g., CR-39) which will enable us to measure recoil protons from intermediate neutron energy interactions that may be of primary importance in the unwanted dose delivered outside the treatment area.

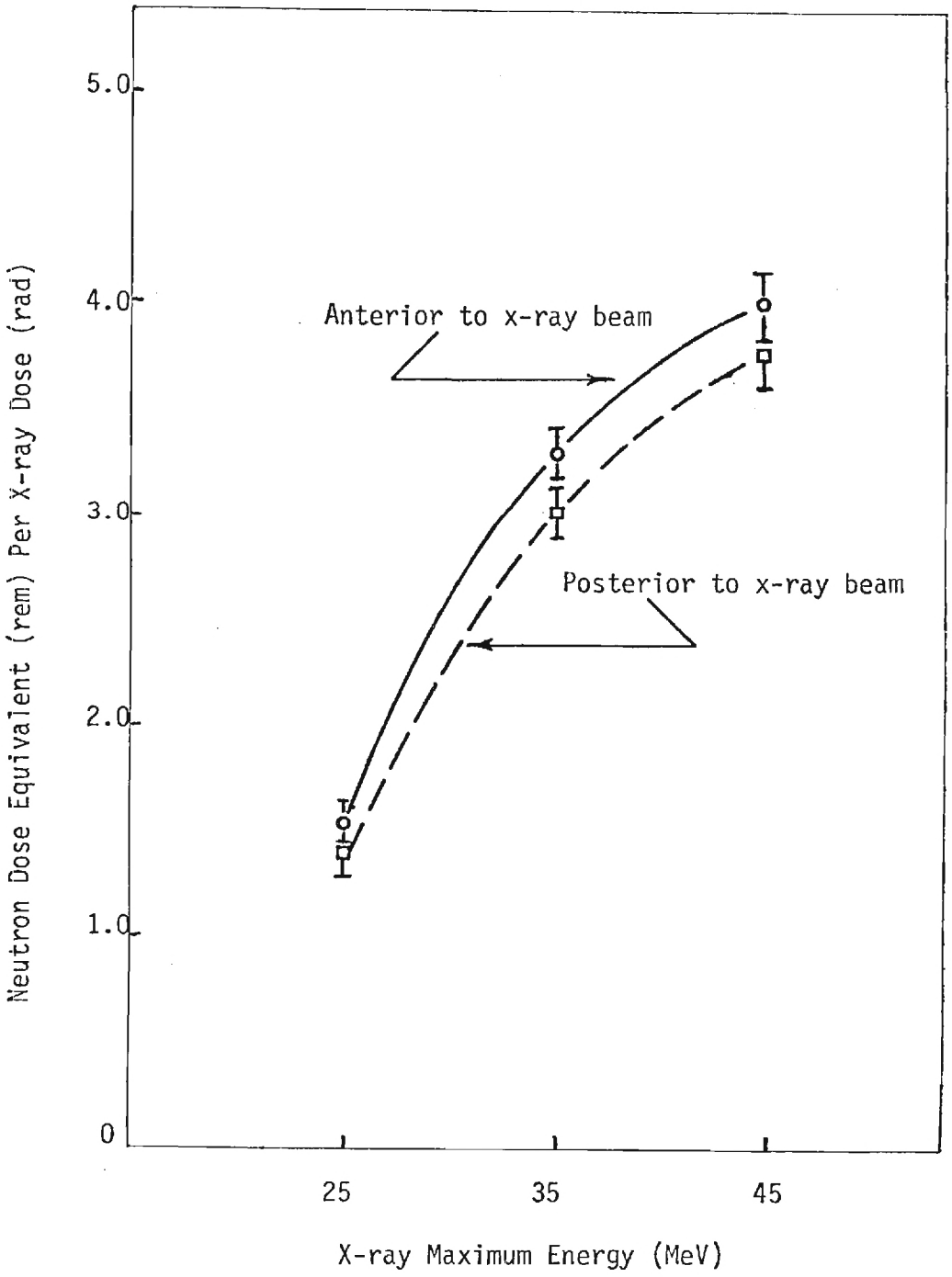

Figure-XVI Change in Neutron Dose Equivalent Per X-ray Dose (rad), from Neutrons Generated in a Heterogeneous Human Phantom as a Function of End Point Bremsstrahlung Energy. Taken at the Bone-Tissue Interface on Bone Surface Anterior and Posterior to Primary X-ray Beam.

4. TWO TRACK-DIAMETER PHENOMENON

This study was initiated due to the somewhat different conclusions two of our previous investigators (Stillwagon and Su) arrived at as to whether the two track-diameter phenomenon exists or not and how the latent tracks are formed in the polycarbonate during alpha particle irradiation.

Stillwagon (1978)[1] first reported that our ECEPF dosimeter was recording two distinct groupings of different diameter tracks during irradiation studies with ^{239}Pu, ^{241}Am, and ^{244}Cm alpha sources. These two sets of tracks varied about a mean diameter of 3.5-4.0 microns for the smaller and 10.0-10.5 microns for the larger as shown in the histogram of Fig. XVII. Stillwagon's data was generated using a source to dosimeter geometry configuration that was enclosed in a vacuum-sealed cylinder in which the air pressure could be varied to control the change in alpha particle energy (due to air absorption) incident on the polycarbonate dosimeter. The source to dosimeter distance was held constant but no collimation was used due to the weak alpha sources used. Consequently, this wide-angle geometry could have produced scatter tracks of various diameters at the detector surface. Stillwagon theorized that these two distinct groupings of tracks were caused (1) by alpha particles with energies near the Bragg peak (as shown in Fig. XVIII) accounting for the small diameter tracks and (2) recoil carbon and oxygen nuclei (from Rutherford scattering with high-energy alphas) accounting for the larger diameter tracks.

In the studies reported by Su (1979)[2] a 2.0 microcurie ^{239}Pu source was used, but the alpha energy incident on the polycarbonate dosimeter was varied by changing the source to dosimeter distance in air at STP. The

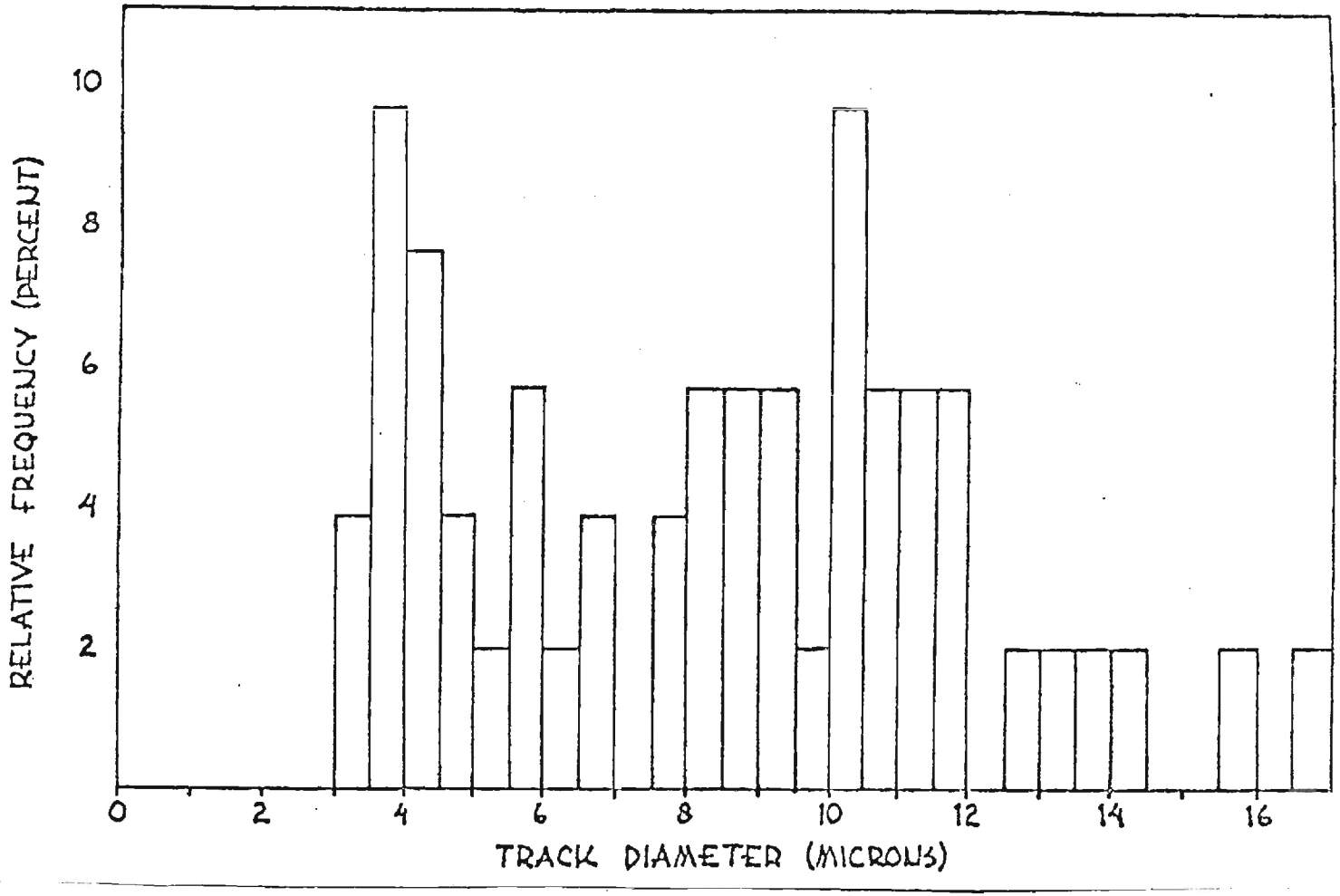

Figure-XVII Relative Frequency of Track Diameters after Alpha Particle Exposure for a Polycarbonate Foil Etched One Hour at 800 V, 2 kHz, 24°C, in 45% KOH. From the Research of Stillwagon (1).

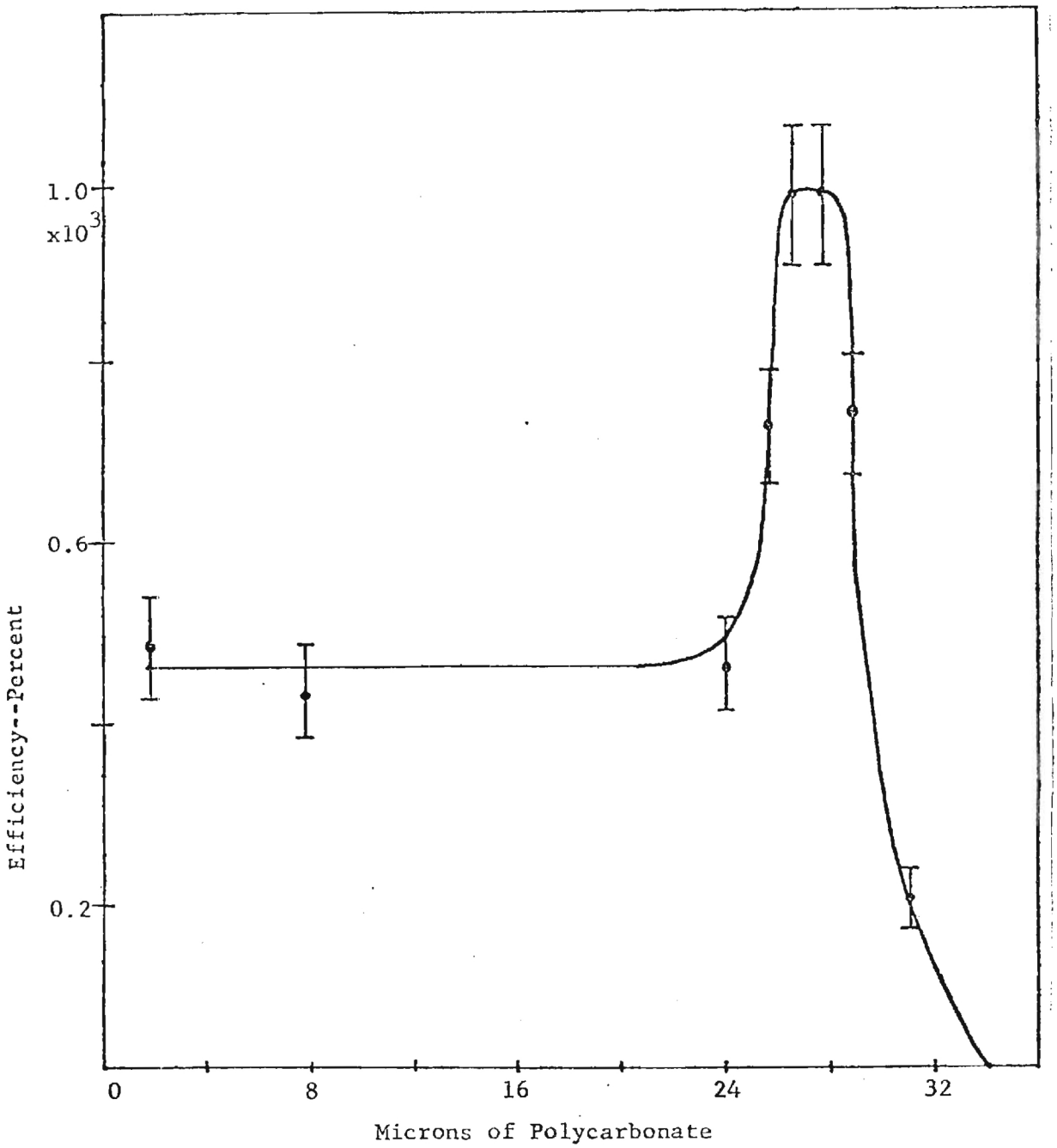

Figure-XVIII Efficiency of Track Production as a Function of Absorber Thickness. Polycarbonate Absorber Thickness was Calculated from g/cm^3 of Air. Count Rate was $1.6516 \times 10^4/24$ hours (from Stillwagon (1))

source to dosimeter distance was collimated; however, the collimator control was somewhat questionable and by definition this arrangement assured a variation of angles at which the alpha particle strikes the foil as the energy distribution was changed with distance. Su's conclusion was, basically, that his research had failed to confirm the existence of the two-track phenomenon. He went on to explain the variation in track diameter seen in his research and exhibited in the histogram of Fig. XIX as a function of the incident alpha energy and the depth in the polycarbonate foil at which the alpha reached its maximum, or Bragg peak, ionization point.

Our research into this question has exhibited that two distinct groups of different diameter tracks do exist in the ECEPF dosimeter foil when used to record alpha particles with energies near the Bragg peak. The experimental apparatus used in this study consisted of a ^{239}Pu source (2.0 microcurie) and dosimeter geometry held constant with a machined 0.5 inch ID collimator; this configuration was enclosed in a vacuum-sealed cylinder in which the air pressure could be varied. To insure that we would be irradiating with alphas near the Bragg peak using this geometry a track production efficiency vs alpha energy (or absorber thickness) curve was generated (see Fig. XX). An Ortec Surface barrier detector connected to a Model 8100 Canberra multichannel analyzer was used as the detector in the geometry described above to determine the total alpha counts and peak energies at various air densities. The Ortec detector was replaced by a 250-micron thick polycarbonate foil in the same geometry position and 24-hour irradiations were taken at the same air densities as used with the Ortec. From a comparision of the polycarbonate data with that of the surface barrier data, an efficiency of track formation as a function of

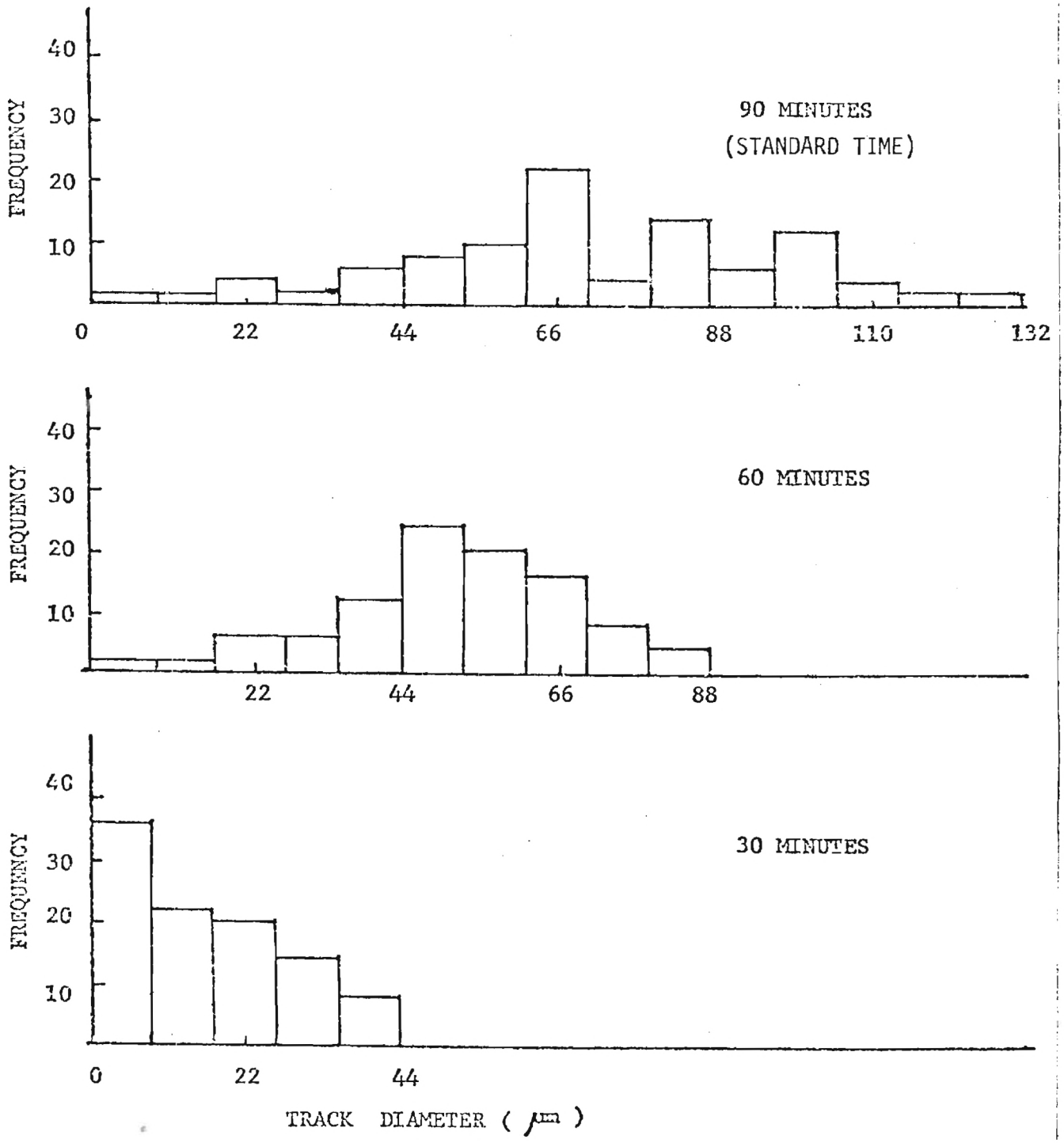

Figure-XIX Relative Track Diameter Distributions of 5.05 MeV Alpha Particles for Different Etching Times under the Standard Etching Conditions as Used by Su (2).

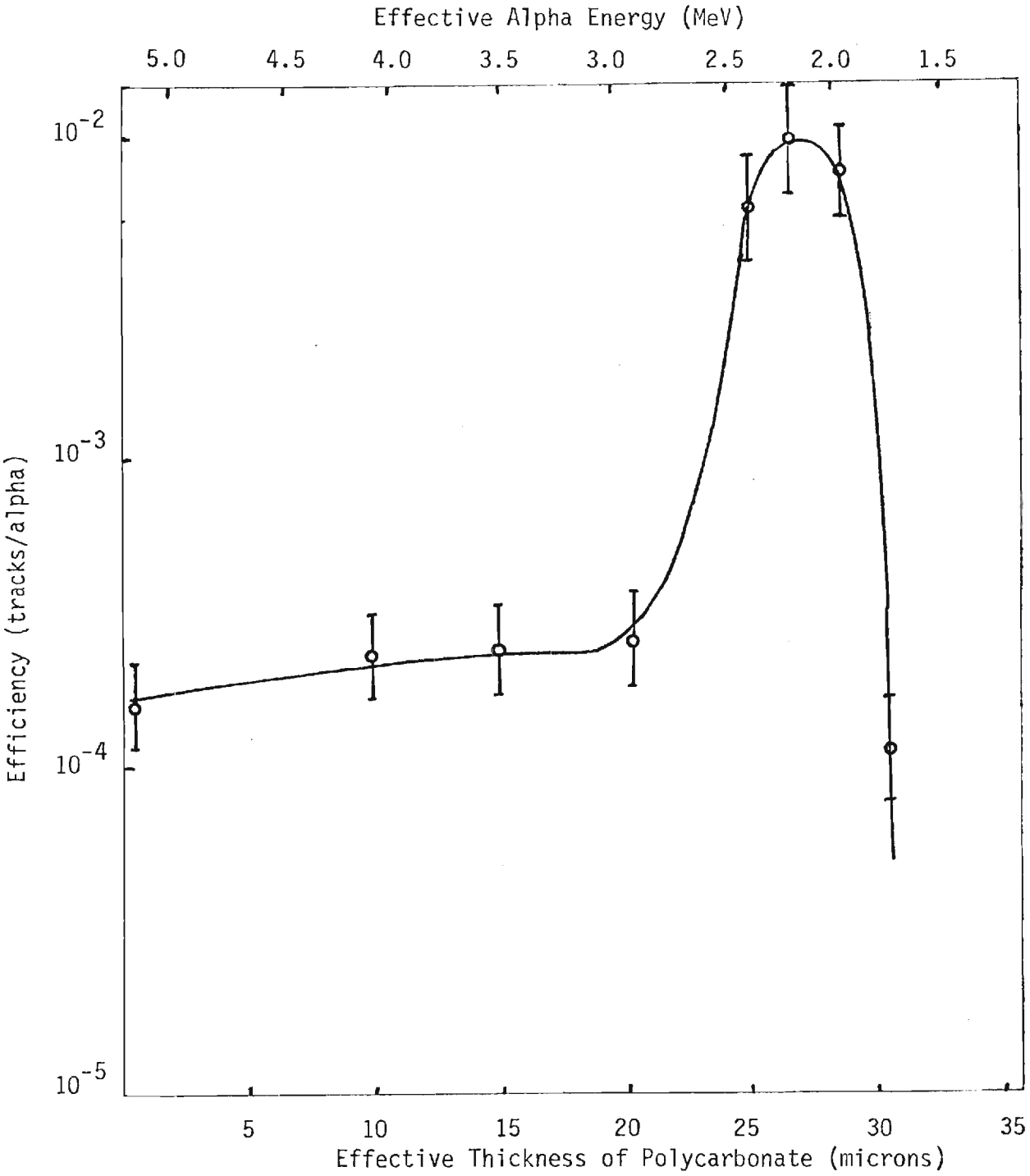

Figure-XX Track Production Efficiency as a Function of Absorber Thickness. Polycarbonate Effective Thickness was Calculated from g/cm^2 Air. Effective Attenuated Alpha Energy Determined by Bethe Curve (30)

equivalent polycarbonate thickness (calculated from the different air densities) was determined. From this curve an air density corresponding to a polycarbonate absorber thickness of $\sim$ 26 microns (and an incident alpha energy of $\sim$2.2 MeV) was chosen as the point of maximum efficiency. Five different 24-hour irradiation measurements were taken using 250-micron thick Transilwrap polycarbonate foil dosimeters. The track diameters in each of the foils were measured using a light microscope with 430X magnification and a Filar micrometer. The result of this investigation, as can be seen in Fig. XXI, clearly shows a frequency of smaller tracks varying about a mean diameter of $\sim$50 microns and a frequency of larger tracks varying about a mean diameter of $\sim$ 90 microns. The difference in absolute track diameters in this research as compared to that of Stillwagon shown in Fig. XVII is due to the increased etch rate and track amplification found using our ECE parameters of an equal volume solution of 45% KOH and C_2H_5OH etched at 1000 V and 2 kHz for ninety minutes at room temperature.

Thus, as stated previously, this research confirms the existence of the two track phenomenon. The next step in this matter is to determine why we are seeing the two track diameters. This is an important consideration since the linear energy transferred (and subsequent dose delivered) on a cellular level would be quite different for a 4 MeV carbon or oxygen recoil (the maximum energy transferred in Rutherford scattering with a 5.1 MeV alpha) as compared with an equivalent energy alpha linear energy transfer. With this type of energy transfer we could have a direct mechanism for chromosome breakage and irreparable damage could be caused in a DNA chain by the constituent atoms simply being knocked out of the chain. Of course, this damage mechanism would be going on in addition to the radial distribution of local dose deposited by secondary electrons as described by

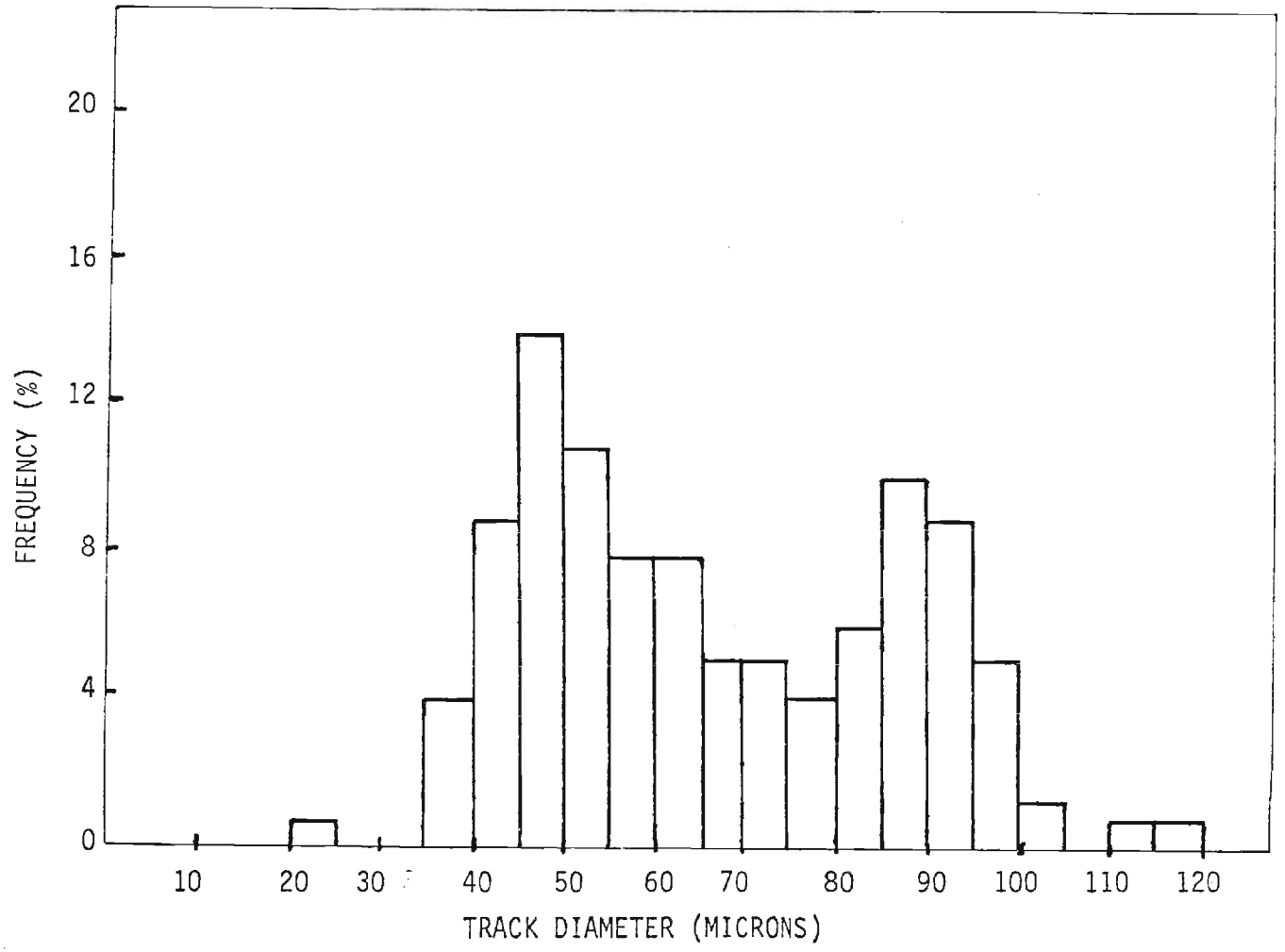

FIGURE-XXI DISTRIBUTION OF TRACK DIAMETERS FOUND IN A POLYCARBONATE FOIL AFTER IRRADIATION BY Pu-239 ALPHAS ATTENUATED TO 2.2 MEV THRU 26 MICRONS OF EEFECTIVE POLYCARBONATE AND ETCHED IN AN EQUAL VOLUME SOLUTION OF 45% KOH AND C_2H_5OH AT 1000 V, 2 KHZ, AT ROOM TEMPERATURE FOR 90 MINUTES.

Katz.[16] Our current studies in this matter are concerned with adapting our polycarbonate casting method (as described later in this report) so as to incorporate various percentage amounts of carbon and oxygen molecules into the original $C_{16}H_{14}O_3$. In this way we will be able to determine the effective importance of recoil nuclei from Rutherford type scattering when the dosimeter is exposed to alpha irradiation.

5. INTERMEDIATE ENERGY NEUTRON STUDIES

The techniques employing electrochemical etching of polycarbonate foils for the measurement of fast and thermal neutron doses have been shown to be both accurate and reliable. Unfortunately, the intermediate neutron energy region is an extremely difficult one in which to evaluate absorbed dose to tissue; and as a result, such dosimetry in the past has been largely neglected. However, we feel this region of neutron energies is important in the field of health physics, especially in our studies of medical high voltage therapy x-ray sources operating at energies <15 MeV.

Our research in this area of intermediate neutron energy so far has been only a continuation of our previous attempts utilizing thermal albedo techniques in conjuntion with ^{6}LiF and ^{10}B thin-tablet radiators and polycarbonate foils.

As we know, the human body is an efficient moderator of neutrons in that a flux of thermal neutrons is produced in and near the body surface when it is irradiated by a fast and intermediate neutron flux. At the point of measurement we must be concerned with two types of thermal albedo neutrons: (1) the component composed of both incident and reflected neutrons initially at thermal energies, the purely thermal albedo, and (2) the albedo component composed of the initially incident neutrons of intermediate and fast energies moderated and reflected by the body to thermal energies.[17]

Utilizing a phantom consisting of a water-filled elliptical cylinder, 20 cm x 30 cm in diameter and 40 cm high (holding $\sim$28 liters of water) and having 0.6 cm thick polyethelene walls,[18] we constructed the dosimeter arrangement as exhibited in Fig. XXII. Each of the dosimeter systems

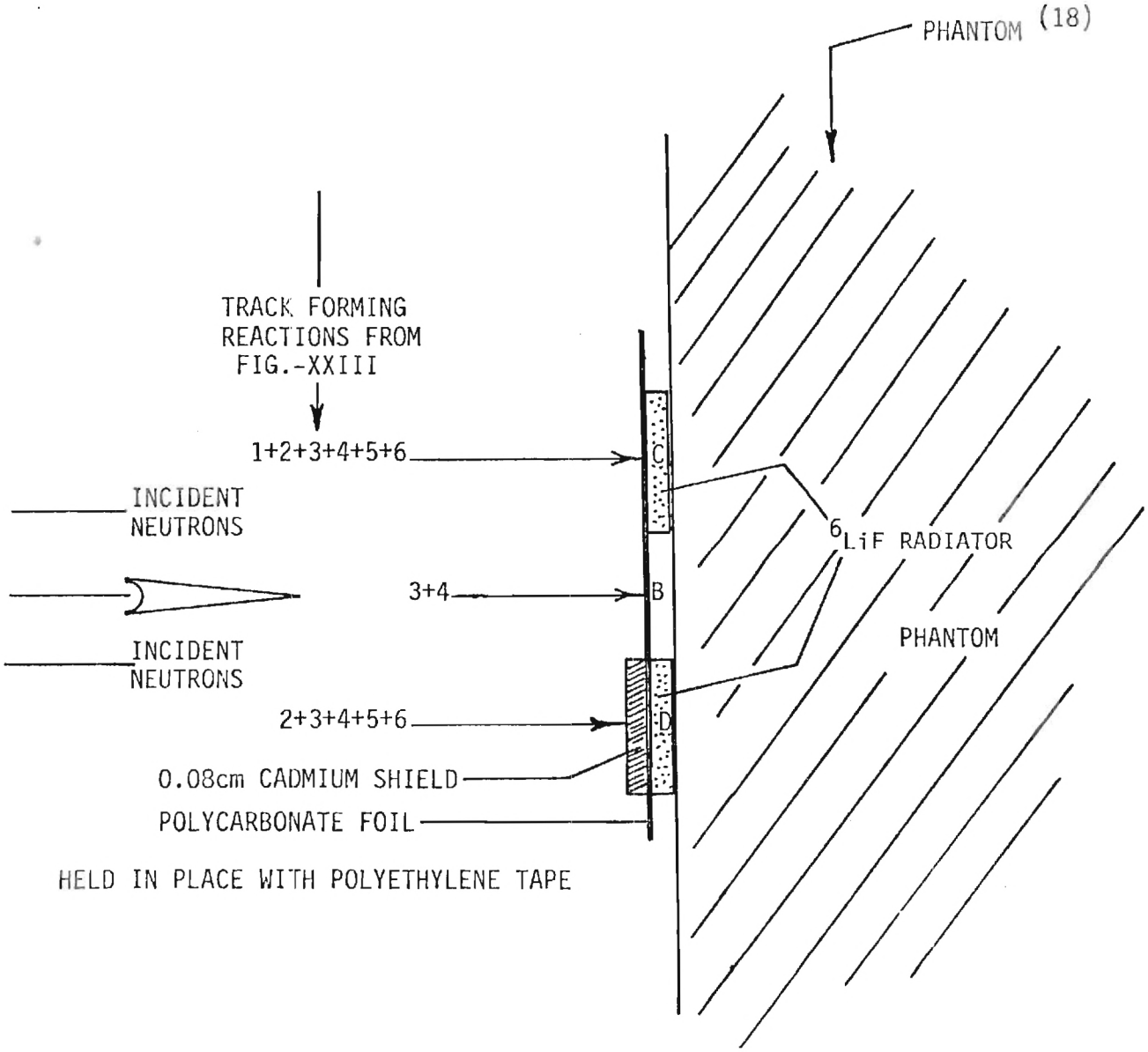

Figure-XXII Albedo Neutron Dosimeter Arrangement for Measurement of the Intermediate Neutron Dose.

consisted of the following arrangement: (A) a bare polycarbonate foil (not shown), in the same plane, adjacent to but not in contact with the phantom (for fast neutron measurement); (B) a bare polycarbonate foil in contact with the phantom surface (fast and reflected fast neutron measurement); (C) an unshielded polycarbonate foil-tablet radiator sandwich, with the radiator in contact with the phantom (measuring, the incident fast and thermal and the albedo fast, thermal, and intermediate components); (D) a 0.08 cm thick cadmium shield--polycarbonate foil--tablet radiator sandwich with the radiator side in contact with the phantom (measuring, the incident fast and albedo fast, thermal, and intermediate components). The maximum number of interactions (due to both incident and albedo neutrons) which will form tracks in the polymer are shown in Fig. XXIII. From Fig. XXII we can see that the difference in track density behind "B" and "D" is due to thermal albedo neutrons from incident thermal, intermediate, and fast neutrons (i.e., (2), (5), and (6) in Fig. XXIII). Thus, the intermediate dose component can be determined by subtracting out the contributions of factors (2) and (6) and obtaining the following equation:[2]

$$H_{int} = \left\{ (N_D - N_B) - \frac{A_T}{\Theta_T} (N_C - N_D) - N_B \left(\frac{A_F n}{(\Theta_F + \gamma)K} \right) \right\} \frac{C_{int}}{nA_{int}} \qquad (1)$$

where,

A_T, A_{int}, A_F = thermal albedo factors for thermal, intermediate, and fast neutrons, respectively,[19]

n = thermal neutron track registration efficiency,[2] $(7.91 \pm 0.82) \times 10^{-4}$)

K = fast neutron track registration efficiency, track/neut.

C_{int} = conversion factor for intermediate neutrons[20] 1.678×10^{-5} mrem/n · cm^2,

1. $n_t^i \xrightarrow{\text{Li-6}}$ H-3 + α

2. $n_t^i \xrightarrow{\text{body}} n_t^a \xrightarrow{\text{Li-6}}$ H-3 + α

3. $n_f^i \xrightarrow{\text{recoil}}$ O + C

4. $n_f^i \xrightarrow{\text{body}} n_f^a \xrightarrow{\text{recoil}}$ O + C

5. $n_e^i \xrightarrow{\text{body}} n_t^a \xrightarrow{\text{Li-6}}$ H-3 + α

6. $n_f^i \xrightarrow{\text{body}} n_t^a \xrightarrow{\text{Li-6}}$ H-3 + α

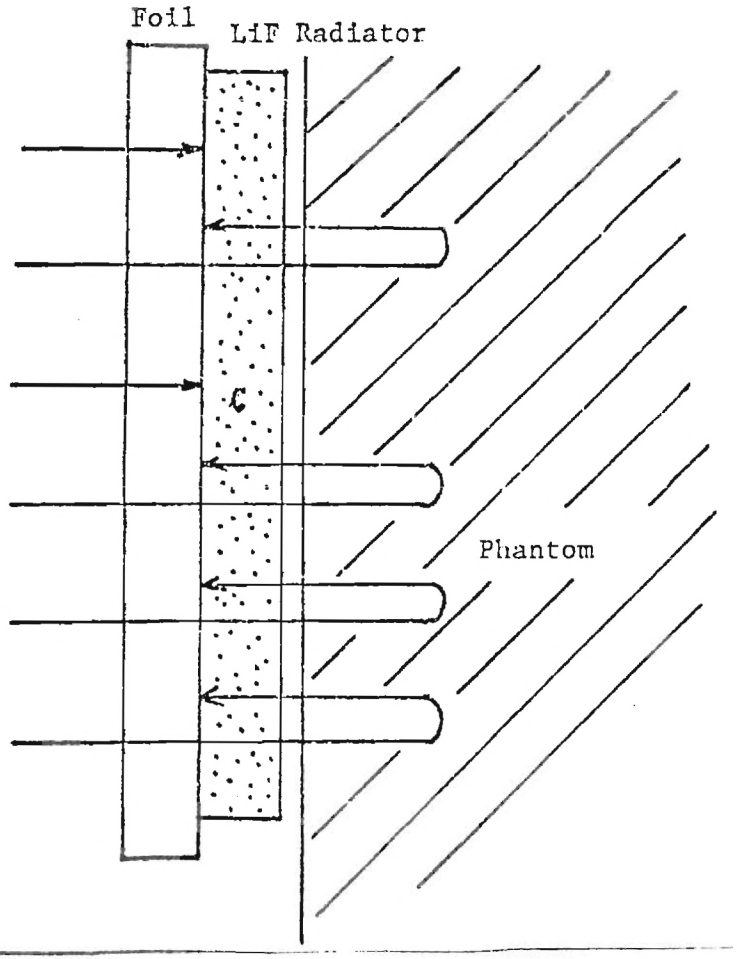

Figure-XXIII Reactions Which Produce Track Densities Behind "C" as shown in the Polycarbonate Dosimeter Configuration of Fig.-XXII. (n_t=thermal neutrons, n_f=fast neutrons, n_e=intermediate neutrons)

Θ_T, Θ_F = directional coefficiency of thermal and fast neutrons (incident direction to albedo direction) Sohrabi, 1975,[23]

γ = fast albedo factor for fast neutrons (number of albedo fast neutrons/number of incident fast neutrons).

A dosimeter system as described here was taped in place on the phantom surface and irradiated at the Health Physics Research Reactor, Oak Ridge National Laboratory. Three different runs were recorded as shown in Table IV with indications of the energy spectrum for no shield, steel shielded and lucite shielded irradiations. The individual polycarbonate foils were electrochemically etched in our standard solution and evaluated. As can be seen in Table V, the intermediate neutron dose-equivalents measured by this technique exhibit unacceptable deviation from the does-equivalent values calculated based upon the neutron spectra shown in Table IV and the dose-equivalent conversion factors in Fig. XXIV.

While we will continue to consider the ECEPF dosimeter in conjunction with albedo techniques and various filtering methods, our current direction of research to hopefully solve the elusive intermediate neutron dose-equivalent measurement problem involves the use of polymers other than polycarbonate which may exhibit lower energy thresholds for track formation. One of these, allyl diglycol carbonate, exhibits a reported proton energy range of track formation from <500 KeV to 1 MeV.[21] Using a polymer such as this we can possibly take advantage of the dominant interaction found with intermediate energy neutrons (i.e., elastic recoils with hydrogen nuclei) using either a proton radiator foil with the polymer or perhaps the polymer alone.

TABLE IV

Calculation of HPRR Spectrum

Group	Upper Energy (eV)	Mid Energy (eV)	N(E) E(*) Run 1 (no shield)	Run 3 (steel shield)	Run 5 (lucite shield)
1	1.49 E7	1.22 E7	2.67 E4	3.77 E4	8.35 E4
2	1.0 E7	8.19 E6	3.31 E5	4.19 E4	9.32 E5
3	6.7 E6	5.77 E6	9.81 E5	1.06 E6	1.11 E6
4	4.97 E6	3.87 E6	4.03 E6	4.38 E6	6.65 E6
5	3.01 E6	2.12 E6	1.05 E7	2.22 E7	1.43 E7
6	1.5 E6	1.16 E6	8.82 E6	3.38 E7	8.22 E6
7	9.07 E5	6.08 E5	1.29 E7	9.36 E7	9.50 E6
8	4.08 E5	2.13 E5	9.48 E6	1.40 E8	7.93 E6
9	1.11 E5	9.80 E4	7.26 E5	5.95 E6	1.07 E6
10	8.65 E4	7.64 E4	5.60 E5	8.11 E6	9.85 E5
11	6.74 E4	5.95 E4	4.20 E5	3.94 E6	8.97 E5
12	5.25 E4	4.63 E4	3.39 E5	3.49 E6	8.35 E5
13	4.09 E4	3.61 E4	2.72 E5	1.57 E6	7.85 E5
14	3.18 E4	2.81 E4	2.35 E5	1.85 E6	7.68 E5
15	2.48 E4	2.19 E4	2.06 E5	6.99 E5	7.11 E5
16	1.93 E4	1.7 E4	1.79 E5	2.82 E5	6.85 E5
17	1.50 E4	1.03 E4	4.43 E5	3.18 E5	1.96 E6
18	7.10 E3	4.88 E3	3.90 E5	2.85 E5	1.87 E6
19	3.35 E3	2.03 E3	4.54 E5	3.24 E6	2.45 E6
20	1.23 E3	8.48 E2	2.92 E5	1.17 E6	1.79 E6
21	5.83 E2	3.54 E2	3.47 E5	1.25 E6	2.38 E6
22	2.14 E2	1.47 E2	2.37 E5	8.77 E5	2.30 E6
23	1.01 E2	6.96 E1	2.18 E5	8.04 E5	1.78 E6
24	4.79 E1	3.73 E1	1.32 E5	4.72 E5	1.18 #6
25	2.90 E1	2.26 E1	1.28 E5	4.67 E5	1.19 E6
26	1.76 E1	1.37 E1	1.22 E5	4.50 E5	1.19 E6
27	1.07 E1	7.34	1.71 E5	5.89 E5	1.79 E6
28	5.04	3.93	1.07 E5	3.58 E5	1.18 E6
29	3.06	2.18	1.35 E5	4.78 E5	1.58 E6
30	1.56	1.25	8.50 E4	3.13 E5	9.76 E5
31	1.0	0.086	7.84 E4	2.56 E5	8.80 E5
32	0.65	0.541	6.80 E4	2.19 E5	7.37 E5
33	0.45	0.212	4.99 E5	1.58 E6	6.86 E6
34	0.1	0.0224	9.41 E5	3.05 E6	5.02 E7
	5.0 E3				

(*) This number is the area of the histogram for each energy interval.

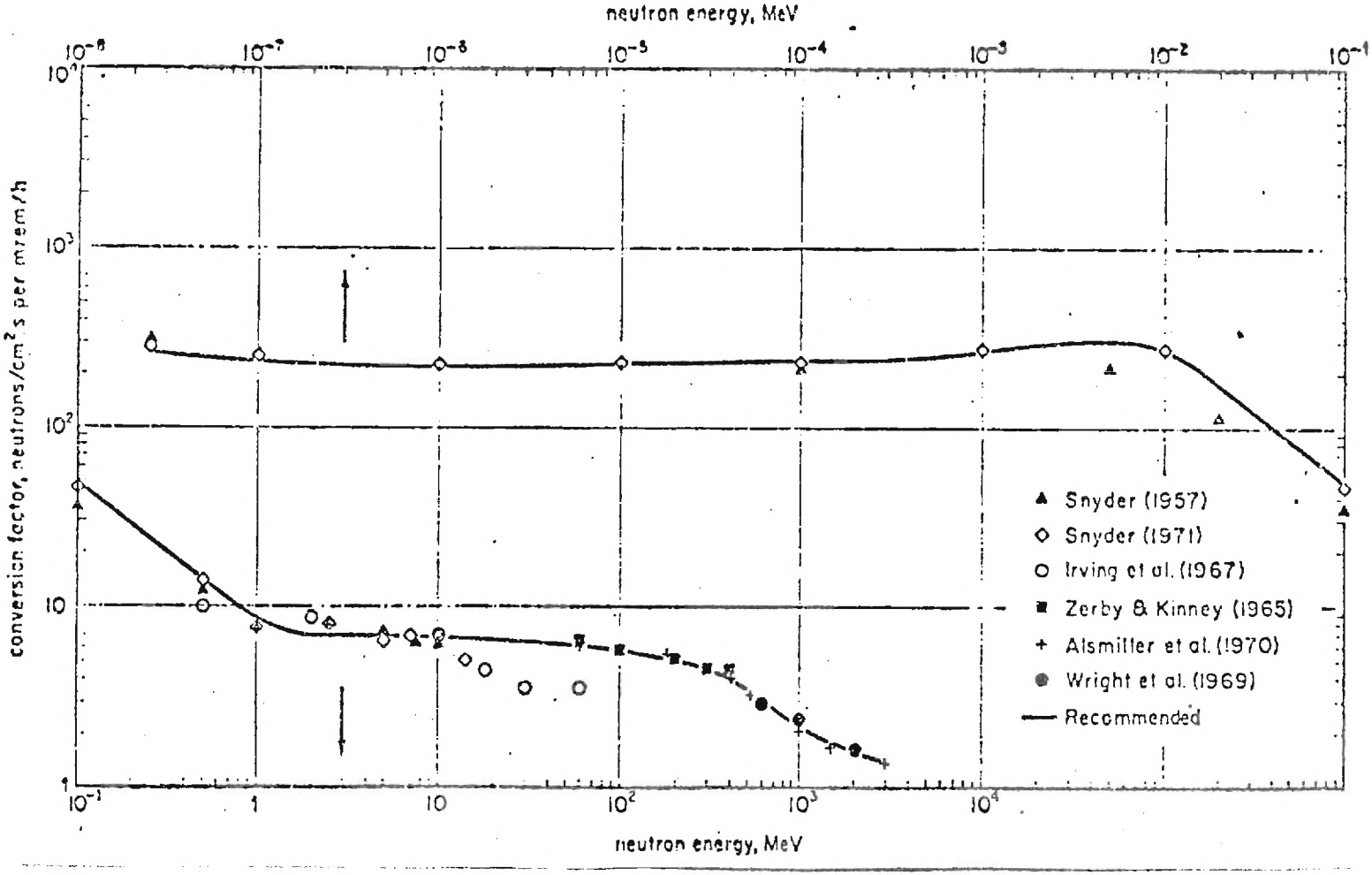

Figure-XXIV Conversion Factors for Neutrons. Unidirectional Broad Beam Normal Incidence. The Curves Indicate the Values Recommended by the ICRP (22)

TABLE V

ECEPF/ALBEDO Measurement of the Intermediate Neutron Dose Equivalent for Different Shielded Runs of the Health Physics Research Reactor at ORNL, Compared to the Calculated Values of Dose Equivalent

RUN	TOTAL FISSION	NET TRACK DENSITY (tracks/cm^2)			MEASURED "H" (mrem)	CALCULATED "H" (mrem)
		N_C	N_B	N_D		
(1) Bare HPRR	1.9×10^{13}	10,017±729	85±67	9,911±725	410±50	484
(2) Steel Shielded HPRR	9.3×10^{13}	28,726±1,234	81±65	28,037±1,219	1,157±620	3,964
(3) Lucite Shielded HPRR	1.9×10^{14}	90,895±2,195	61±57	78,970±2,046	2,273±1,824	660

6. BORON NEUTRON CAPTURE THERAPY (BNCT)

The Boron Neutron Capture Therapy (BNCT) studies at the Georgia Tech Research Reactor are steadily progressing toward clinical trials. Though the therapy is potentially applicable against many types of tumors, current emphasis is being directed toward the treatment of the malignant brain tumor, glioblastoma multiformae. This particular grade of tumor is characterized by a central necrotic tumor mass from which project numerous fingerlets into adjacent healthy brain tissue, making it particularly difficult to successfully treat with surgery or gamma radiation.

BNCT has been proposed as an alternative therapy whereby a ^{10}B-loaded compound injected into the patient is preferentially taken up by the tumor, but is prevented from infiltrating the healthy brain tissue by the blood brain barrier. The head is then irradiated with an epithermal neutron beam, which is thermalized by the time it reaches the tumor. The reaction particles produced from the $^{10}B(n, \alpha)^{7}Li$ interaction within the tumor thus irradiates the cancerous tissue in a very localized manner, keeping the dose to the surrounding healthy tissue to a minimum.

An epithermal beam port has been designed and constructed over the past year and is in place at the Georgia Tech Research Reactor (GTRR). The beam remains to be characterized as to its γ-contamination as well as its neutron energy spectrum. Our developments in the fast and thermal capabilities of the ECEPF dosimeter are presently being used to help in this task. At the same time a biological dosimeter is being developed to determine the RBE of the combined radiations in the beam.

At present, polycarbonate foils are being used to calibrate a system to determine the level of ^{10}B in the patient's blood at the time of

epithermal neutron irradiation so that the neutron fluence for effective therapy can be determined. Small polycarbonate foils are placed in plastic vials containing various concentrations of boric acid. The vials are then irradiated at a thermal neutron port with a known fluence, etched, and inspected for alpha tracks from the $^{10}B(n, \alpha)^{7}Li$ reaction. From this data, a calibration curve of ^{10}B concentration vs track density will be generated, from which ^{10}B blood levels can be determined during future clinical trials.

A more complex problem is to determine the ^{10}B distribution in the tumor mass. Studies must be conducted on test animals to determine where and to what degree the compound concentrates, as well as the uniformity of the distribution within the central tumor mass as compared to the fingerlets. Our group currently has a sample of the most promising ^{10}B compound which will be injected into rats and beagles with induced tumors. The animals will then be sacrified and tissue sections from the tumors will be placed on sections of polycarbonate foils and irradiated at the thermal neutron port. The etched foils' reaction alpha tracks will serve as indicators of the ^{10}B.

Studies are also underway to evaluate the depth dose of fast, intermediate, and thermal neutrons in several tissue-equivalent phantoms to determine the actual neutron fluence as well as contributions present at various distances into the brain.

7. Thermal Neutron Dosimetry

The ^{6}LiF radiator tablet--polycarbonate foil--thermal neutron dosimeter developed earlier in our research has provided an extremely sensitive and reliable method to measure the thermal neutron dose-equivalent. Unfortunately, the use of ^{6}LiF (or ^{10}B) tablet radiators has several inherent problems; namely, the hydroscopicity and fragility of the thin tablets and the poor spatial response of the dosimeter configuration. To help eliminate these unwanted characteristics and at the same time keep the desirable aspects of the dosimeter (i.e., sensitivity $<$ 1 mrem) we are perfecting a polycarbonate casting method which will allow us to incorporate the charged particle radiator compound into the foil itself. Our procedure for this technique is as follows.

A smooth pane of plate glass (30 cm x 30 cm) is cleaned with toluene and coated with a thin uniform film of glycerin (we use a dip bath of dissolved cherry jell-o). The glycerin coat is allowed to dry. A section of standard 250-micron thick polycarbonate is dissolved in a suitable solvent (e.g., toluene or acetone) under a laboratory hood. The desired "loading solution" is then mixed with the dissolved polycarbonate. In order to achieve a uniform distribution of "loadant", the compound should be soluble in the same solvent as the polycarbonate. A puddle of the loaded polycarbonate solution is placed on the glycerin-coated glass plate and spread to the desired uniform thickness by using a "doctor blade". The glass plate and polycarbonate film coating is covered, to protect from dust collection, and allowed to dry. We then cut the dry "loaded" polycarbonate film into the desired dosimeter sizes, immerse the entire plate in a warm water bath and the individual sections of polycarbonate float to the water surface as the glycerin layer dissolves.

Perfecting our casting and loading technique has, necessarily, been a learning process. However, we are progressing steadily towards our initial thermal irradiation evaluations. This technique affords our reserach much freedom (from suppliers minimum order requirements) and is applicable to questions involved in several areas of our research; such as, thermal neutron dosimetry, intermediate neutron dosimetry, and recoil nuclei studies.

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PROJECT PERSONNEL

MORGAN, KARL Z.

Professor at Georgia Institute of Technology

Karl Ziegler Morgan was born in Enochsville, North Carolina, on September 27, 1907. He received the A.B. and M.A. degrees from the University of North Carolina in 1929 and 1930, respectively, and the Ph.D. degree in physics from Duke University in 1934. From 1934 to 1943 he was chairman of the Physics Department of Lenoir Rhyne College, and during this period did research in cooperation with Duke University in the field of cosmic ray showers, the meson lifetime, etc., in Linville Caverns, on Mt. Mitchell, Beech Mountain, Mt. Evans, etc.

He joined the Metallurgical Laboratory staff at the University of Chicago in the spring of 1943. Here he was one of a group of six persons who developed and established the new science and profession of health physics. During the fall of 1943, he transferred to Oak Ridge National Laboratory where, until the latter part of 1972, he was Director of the Health Physics Division which was engaged in research, engineering, and applied problems. Upon leaving Oak Ridge National Laboratory, he joined the faculty of the Georgia Institute of Technology as Neely Professor in the School of Nuclear Engineering.

In 1956, he was the first president of the Health Physics Society, and from 1966 to 1970 was the first president of the International Radiation Protection Association which has about 10,000 members in some 65 countries. He now is President Emeritus of IRPA, an Emeritus member of the Main Commission of ICRP and of NCRP. For twenty years he was chairman of the committees of ICRP and NCRP dealing with maximum permissible internal dose of radioisotopes. He has published over 300 papers dealing with subjects of cosmic rays, radiation protection, instrumentation, internal dose, effects of low-level radiation exposure and general health physics. He is author of chapters in some twenty text books. He is past editor of the journal HEALTH PHYSICS.

In 1962, K. Z. Morgan and W. Binks (England) were awarded the first gold medals for meritorious work in the field of radiation protection by the Royal Academy of Science of Sweden.

Dr. Morgan received the Distinguished Alumni Award and the honorary Doctor of Science Degree from Lenoir Rhyne College, honorary membership in Sigma Pi Sigma from Berea College, and the First Distinguished Service Award of the Western Chapter of the Health Physics Society. He is a member of the Health Physics Society, the International Radiation Protection Association, the American Public Health Association, the American Association for the Advancement of Science, the American Industrial Hygiene Association, the Research Society of America, the Radiation Research Society, an Associate Fellow for the American College of Radiology, a Fellow of the American Physical Society and of the American Nuclear Society.

A Selection of Recent Reports and Publications

Over 300 papers and publications have been written. A sampling of these over the past few years is as follows:

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BIOGRAPHICAL SKETCH

SANDERS, MICHEAL E. -- Ph.D. Candidate, School of Nuclear Engineering

Education

A.B., Radiation-Nuclear Technology, Oklahoma State	1967
A.B., Journalism, Ohio State University	1973
B.S., Health Physics, Oklahoma State	1978
M.S., Applied Nuclear Science, Georgia Institute of Technology	1979

Employment History

Industrial Nucleonics, Columbus, Ohio, Applied Physics	1967-73
A. G. Edwards and Sons, Tulsa, Oklahoma, Stockbroker	1973-76
Oklahoma State, Stillwater, Oklahoma, Lab Asst.	1976-78
Georgia Inst. of Technology, Atlanta, Ga., Grad Res. Asst.	1978-present

Experience Summary: While working for Industrial Nucleonics, Columbus, Ohio, was involved in applied research and design of process measurement and control systems utilizing beta, gamma, and x-ray sources. He was also responsible for the health physics practices of the Applied Physics laboratory. Since coming to Georgia Tech, has been a graduate research assistant concerned with development and application of the electrochemical etching of polycarbonate foils. He is a member of the Health Physics Society and the American Association of Physicists in Medicine.

Major Reports and Publications

1. "Thermal Neutron Dosimetry Using Electrochemical Etching," Paper P/11 presented at 24th Annual Meeting of Health Physics Society, Philadelphia, Pennsylvania, 1979 (Best Paper Award).
2. "Neutron Contamination in Medical Therapy Accelerators," a paper presented at 46th Meeting of Southeastern Section of the American Physical Society, Chattanooga, Tennessee, 1979.
3. "Photoneutron Contribution from the Thermal Neutron Shield in a Typical Activation Foil Neutron Detector Exposed to a 33 MV X-ray Therapy Beam," to be published in Medical Physics Journal (1980).
4. "Measurement of Neutron and Charged Particle Contamination in High-Energy Medical Therapy X-ray Beams Using Recoil Particle Track Formation in Polycarbonate Foils," paper presented at 25th Annual Meeting of Health Physics Society, Seattle, Washington (1980)

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BIOGRAPHICAL SKETCH

NOONAN, DENISE JANE -- Ph.D. Candidate, School of Nuclear Engineering

Education

B.S., Physical Sciences, Colorado State	1976
M.S., Health Physics, Georgia Institute of Technology	1979

Employment History

College of Veterinary Medicine, Colorado State, Research Asst.	1974-76
School of Nuclear Engineering, Georgia Insti. of Tech., Research Asst.	1979-

Experience: While working at Colorado State, was involved in reserach dealing with bone remodeling in uremic dogs; uremia induced by prenatal irradiation of fetus. Since becoming a GRA at Georgia Tech, has been concerned with boron neutron capture therapy and epithermal neutron measurement. Over the past year, has been working on chromosome breaks in tradescantia microspores as a biological dosimeter. Has also worked as GTA, teaching the Radiation Detection laboratory for undergraduates at GIT. Is a member of the Phi Beta Kappa Honor Society and was the recipient of the CSU Faculty Honors Award, President's Fellowship (CSU), and President's Fellowship (GIT), and is also a member of the Health Physics Society.